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HANDBOOK ON RESERVOIR RELEASES FOR FISHERIES AND ENVIRONMENTAL QUALITY

by

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This instruction report identifies and discusses many of the downstream environmental quality effects of general reservoir project operation, peaking hydropower operation, and flood control operation. Individual design and operation elements are identified, when possible, and the specific environmental effects of each are detailed under topic headings. Some of the topics

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addressed in this handbook include the effects of daily and weekly minimum low flows, effects of fall drawdown, effects of highly fluctuating flows, and relative effects of surface versus deep release. Each topic is defined and discussed; recommendations are presented which, in many cases, will alleviate the detrimental environmental quality effects of reservoir project operation.

PREFACE

The initial draft of this report was prepared by the East Central Reservoir Investigations (ECRI), National Reservoir Research Program (NRRP), US Fish and Wildlife Service (FWS), Bowling Green, Ky., with the assistance of the Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES), under interagency agreement (FWS Agreement No. 14-16-0009-82-1809). After the NRRP was disbanded by the FWS in Fiscal Year 1983, this report was completed by the EL of the WES and reviewed by Aquatic Ecosystem Analysts (AEA) under Purchase Order No. DAEN39-84-M-1894. The AEA is staffed by former members of the NRRP.

This study forms part of the Environmental and Water Quality Operational Studies (EWQOS), Task IIB, Guidelines for Determining Reservoir Releases to Meet Environmental Quality Objectives. The EWQOS Program is sponsored by the Office, Chief of Engineers (OCE), US Army, and is assigned to WES under the management of EL. The OCE Technical Monitors were Mr. Earl E. Eiker, Dr. John Bushman, and Mr. James L. Gottesman.

This report was written by Dr. John M. Nestler of the EL and Messrs. Charles H. Walburg, Jerry F. Novotny, Kenneth E. Jacobs, and William D. Swink of the ECRI. Technical review was performed by Drs. James Martin and Marc Zimmerman. Editorial review was performed by Ms. Jessica S. Ruff of the WES Information Products Division. Mr. Charles Walburg was the chief of ECRI and Mr. Robert M. Jenkins was the director of NRRP. This report was prepared under the direct supervision of Dr. Nestler, EL, WES, and under the general supervision of Mr. Mark Dortch, Chief, Water Quality Modeling Group, EL; Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division, EL; and Dr. John Harrison, Chief, EL. Dr. Jerome Mahloch was Program Manager of EWQOS.

This report was prepared for use by Corps of Engineers (CE) scientists as an aid in understanding the often complex effects that reservoir operation can have on downstream environmental quality. This report presents descriptions of many of the most pressing environmental issues faced by the CE in the design and operation of reservoirs. Many recommendations are provided that will maintain and protect downstream environmental quality while allowing reservior projects to meet authorized purposes.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

This report should be cited as follows:

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
square feet	0.09290304	square metres

HANDBOOK ON RESERVOIR RELEASES FOR FISHERIES AND ENVIRONMENTAL QUALITY

PART 1. INTRODUCTION

1.1 Background

1.1.1 The US Army Corps of Engineers (CE) develops and manages water resources in a manner consistent with environmental quality in accordance with laws and policy established by Congress and the Administration. That is, the CE considers and seeks to balance the developmental and environmental needs of the Nation (US Army Corps of Engineers 1983).

1.1.2 As part of its role in the development of water resources, the CE operates reservoir projects to fulfill authorized project purposes such as flood control, water supply, navigation, power generation, and recreation. The operation of reservoir projects can cause considerable alteration in preimpoundment conditions. The storage and release of impounded water not only floods the river upstream from the dam but also modifies the immediate downstream reaches, or tailwater. Project operation may modify preimpoundment flows, channel morphology, temperatures, and concentrations of dissolved gases and other water quality conditions in the tailwater and may thereby significantly alter or disturb the downstream aquatic ecosystem. Development of water resources by the CE through the operation of reservoir projects, in a manner that is consistent with environmental quality, can be achieved by avoiding or ameliorating the negative downstream effects of reservoir project operation. Environmental quality objectives downstream of reservoir projects can be achieved by:

a. Identifying general and site-specific impacts associated with each design and/or operational alternative in the planning stages so that the least detrimental alternative can be selected.

b. Identifying predictive methods that can be used to quantify the effects of different design and/or operational alternatives.

c. Developing or identifying methods and techniques that ameliorate the detrimental downstream effects of reservoir project operation.

d. Formulating and implementing reservoir release guidelines that maintain or improve conditions in the tailwater ecosystem.

1.2 Problem

1.2.1 Two major factors complicate efforts to achieve downstream environmental quality objectives. First, most CE projects are unique; that is, they are designed and operated under multiple, site-specific economic, hydraulic, and social constraints. Reservoir projects are operated for different purposes, have different gate and valve configurations, are of various sizes and depths, and are located at different altitudes and latitudes. Consequently, identification of general impacts of project operation on tailwaters is difficult as is the concomitant formulation of generalized recommendations and guidelines to meet downstream environmental quality objectives.

1.2.2 Second, methods available for determining the quality, quantity, and timing of reservoir releases necessary to maintain the tailwater ecosystem may not be widely known or disseminated. Additionally, in some cases the environmental requirements of tailwater biota are either poorly known or widely scattered in scientific journals and reports prepared by governmental agencies and public utility companies. The information necessary to quantify the degree to which modifications in flow, temperature, dissolved gases, and other water quality characteristics affect the composition and abundance of aquatic organisms in tailwaters is similarly unknown or not readily available.

1.3 Solution

1.3.1 Formulating effective, generalized reservoir release guidelines that meet downstream environmental quality objectives first requires that the complex design and operation of reservoir projects be crystallized into separate and distinct operational procedures and design elements that can be individually examined and studied to determine their effects on the downstream aquatic environment. Then, based on this examination, guidelines and recommendations can be formulated that minimize the deleterious downstream effects of each operational procedure or design element. This approach avoids the difficulties associated with simultaneously addressing all downstream environmental effects associated with reservoir projects. It also allows guidelines to be formulated at a level more likely to allow development of water resources consistent with environmental quality objectives. For example, a tailwater downstream from a peaking hydropower project receives minimum low-flow releases when demand for power is low, experiences rapid changes in water quality and quantity at start-up, and receives maximum flows during power generation. Each of these operational procedures is discrete, applicable to most peaking power projects, and the associated environmental impacts can be quantified or described. Operational or structural alternatives that are consistent with project purposes and maintain downstream environmental quality can be identified. Discharge of a minimum release designed to maintain a target species during nongeneration as well as staging the start-up of turbines during the beginning of a generation cycle in order to prevent scour and entrainment can alleviate some of the detrimental effects associated with peaking hydropower operation. Thus, a water resource is developed by generating peaking hydropower while simultaneously maintaining downstream environmental quality.

1.3.2 This approach requires identification of discrete components of project design and operation. A list of the separate design elements and operational procedures that have major downstream environmental consequences was tentatively identified in meetings attended by personnel from the US Army Engineer Waterways Experiment Station (WES), and the US Army Engineer Divisions, Missouri River (MRD), Ohio River (ORD), and South Atlantic (SAD). This list was then transmitted as a survey to District and Division offices for ranking, comments, revisions, and incorporation of additional material. Survey results were carefully evaluated and the list of topics was modified to incorporate the input from CE field offices. The modified list serves as a general outline for this handbook with each element in the list becoming a specific topic area.

1.3.3 The information needed to address the topic areas identified by the survey was obtained from documents prepared as part of the Environmental and Water Quality Operational Studies Program, Work Unit IIB, Reservoir Releases. These documents synthesize available literature and describe results of field studies. Literature information was obtained from an annotated bibliography (Walburg et al. 1981a) and a literature review (Walburg et al. 1981b). Generic impacts of reservoir releases were verified in field studies of water quality, benthos, and fish at seven study sites that differed in design, location, and purpose (Walburg et al. 1983). The study sites are representative of many CE reservoir projects in the southeastern United States and some projects in other regions. Intensive, short-term studies were performed to refine or assess methods (Nestler et al. 1985) or describe the effects of operational procedures for which little or no documentation was available in the literature (Matter et al. 1983; Novotny and Hoyt 1983; and Barwick, Hudson, and Nestler 1985).

1.4 Application

1.4.1 The information and guidelines presented in this handbook can be used to address many of the environmental quality issues related to flood control and peaking hydropower operation for existing projects, projects scheduled for modification, and projects that are in the planning stages. The handbook is designed for use by CE scientists requiring specific information on topic areas associated with reservoir discharges. Examples of applications of this document include but are not limited to:

- a. Evaluation of the relative merits of deep release versus surface release for a project in the planning stages.
- b. Design of studies to estimate flow requirements downstream of reservoir projects.

c. Description of the effects of generating flows on the tailwater ecosystem.

A complete list of topic areas can be found in the Contents (page 3). The first-time user of this document should note the topics in Part 2 and skim the topic entitled "Differences Between Tailwaters and Rivers" (pages 14-20).

1.4.2 Additionally, the user may peruse this entire handbook to obtain an understanding of the types of effects that reservoir project operation can have on the downstream ecosystem. This understanding can then be used to implement studies designed to identify site-specific effects or to identify the least environmentally disruptive of several design and operation alternatives.

1.5 Organization

1.5.1 The topics addressed in the handbook include those that are general in nature and transcend single project purposes (Part 2); those concerning peaking hydropower operation (Part 3), and those concerning flood control operation (Part 4). This organization enhances the usefulness and flexibility of this document because: (a) topic areas of interest can be easily located, (b) necessary information can be obtained without reading the entire document, and (c) updating is simpler as additional topics or sections can be added easily.

1.5.2 Each topic area is organized for ease of use. A topic associated with reservoir releases is introduced as a simple statement. For example, impacts of and recommendations for streamflows to meet instream flow needs downstream from peaking hydropower projects are discussed under the heading, "Impacts of Daily and Weekly Minimum Low Flows" (section 3.2). Each topic statement is followed by one or two paragraphs (the "Topic Description") that fully describe the operational procedure impacting the tailwater ecosystem. These paragraphs are designed to define and delineate the question, thereby ensuring the proper utilization of the concluding recommendations.

1.5.3 A comprehensive discussion follows the "Topic Description," describing factors and interactions that characterize the effects of a specific operational procedure. The different environmental effects of project design and operation that are observed at most CE reservoir projects with similar purposes are identified. Site-specific impacts of reservoir project operation, such as reservoir processes that alter the quality of releases, are discussed; natural phenomena that may alter the quantity and quality of reservoir releases as they proceed downstream are also mentioned.

1.5.4 A final "Recommendations" section provides guidance on the topic area. This last section also identifies predictive methods for quantifying the effects of a specific design or operational alternative because, in some cases, site-specific considerations may negate the utility of general guidelines.

1.5.5 This document represents the distillation of many technical reports, a large amount of other scientific literature, and field observations. It is quite possible that the downstream environmental effects associated with a specific reservoir project may not exactly reflect the subjective treatment provided in this handbook. There is no substitute for a commonsense approach to downstream environmental quality concerns, including carefully planned studies to detail the downstream effects of a particular project. Numerous methods are available to aid in the selection of the most environmentally sound design and operational alternatives (see paragraphs 2.3.2.1 to 2.3.2.11 in the section entitled "Useful Simulation Techniques for Reservoir Release Applications"). The large amounts of funds spent to design, construct, or modify a reservoir project may be partly wasted if insufficient attention is paid to downstream environmental quality concerns resulting in the loss of downstream aquatic resources, expensive postauthorization modifications, and lengthy litigation.

1.5.6 There is an inexorable connection between in-pool and downstream environmental quality concerns. Uninformed efforts to enhance the tailwater ecosystem may conflict with recreation, water quality, and fishery resources in the reservoir. Therefore, efforts to ameliorate the downstream effects of reservoir project operation must also consider the consequences of these actions on the environmental quality of the reservoir.

1.6 References

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Matter, W. M., Hudson, P. L., Nestler, J. M., and Saul, G. E. 1983. "Movement, Transport, and Scour of Particulate Organic Matter and Aquatic Invertebrates Downstream from a Peaking Hydropower Project," Technical Report E-83-12, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Nestler, J. M., Milhous, R. M., Troxel, J., and Fritschen, J. 1985. "Instream Flow Needs for Fish, Fishing, and Recreation Below Buford Dam, Georgia: A Case History Study," prepared by US Fish and Wildlife Service and Environmental Laboratory for US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

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US Army Corps of Engineers. 1983. "Digest of Water Resources Policies and Authorities," Engineer Pamphlet 1165-2-1.

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Walburg, C. H., Novotny, K. E., Jacobs, K. E., Swink, W. D., and Campbell, T. M. 1981a. "Water Quality, Macroinvertebrates, and Fisheries in Tailwaters and Related Streams: An Annotated Bibliography," Technical Report E-81-8, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

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PART 2. GENERAL TOPICS

2.1 Background

2.1.1 This section includes several categories of topics associated with reservoir operation that are general in nature and not related specifically to a single project purpose.

2.1.2 The topics in this part of the report can be organized into three general categories. The first category includes design and operation aspects that are universal among CE projects, for example:

- a. The generic environmental effects associated with either deep release or surface release are generally independent of the authorized purpose(s) of the project.

- b. Conduit inspections are routinely carried out on all reservoir projects that discharge water through conduits, whether the projects are operated for flood control or hydropower generation.

2.1.3 The second category of topics includes physical and chemical phenomena that are associated with all types of impoundments. For example, topics in this general area include descriptions of major differences between rivers and tailwaters and a discussion of both armoring and sedimentation processes in tailwaters.

2.1.4 The third category includes management and operational strategy topics. These topics include proper selection of target species, actions to follow if a project is unable to simultaneously meet more than one of several downstream water quality objectives, and general descriptions of simulation codes for addressing environmental quality problems downstream from CE reservoir projects.

2.1.5 A general treatise on reservoir limnology is not included in this handbook since numerous limnological textbooks cover this topic (Cole 1984; Hutchinson 1957, 1967, 1975; US Army Corps of Engineers 1985; Wetzel 1975). A basic grasp of reservoir limnology is of particular importance to understanding the downstream effects of reservoir releases. In most cases, downstream water quality is determined predominantly by limnological processes occurring at the depth of withdrawal. For example, understanding the downstream effects of deep release requires a knowledge of biological, physical, chemical, and mixing processes occurring in the hypolimnion of a reservoir. To completely understand many of the reservoir release problems, particularly those concerning water quality, one should have available at least one general limnology textbook.

2.1.6 References

Cole, G. A. 1984. Textbook of Limnology, C. V. Mosby Company, St. Louis, Mo.

Hutchinson, G. E. 1957. A Treatise on Limnology, Vol I: Geography, Physics, and Chemistry, John Wiley and Sons, New York.

________. 1967. A Treatise on Limnology, Vol II: Introduction to Lake Biology and the Limnoplankton, John Wiley and Sons, New York.

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Wetzel, R. G. 1975. Limnology, Saunders College Publishing, Philadelphia, Pa.

2.2 Differences Between Tailwaters and Rivers

2.2.1 Topic Description

Reservoir projects may greatly modify preimpoundment riverine conditions in the tailwater. However, aquatic communities in tailwaters can be diverse and productive, and many tailwaters support valuable sport fisheries. Sufficient information is currently available to formulate reservoir release guidelines for planning, designing, and operating reservoir projects to achieve downstream environmental quality objectives while simultaneously meeting authorized project purposes. However, efforts to minimize negative downstream effects of reservoir operation must be based on a fundamental understanding of how dams modify the tailwater ecosystem from preimpoundment conditions.

2.2.2 Discussion

2.2.2.1 Reduced mixing in reservoirs, in contrast to highly mixed riverine flows, often results in seasonal reservoir stratification which, in turn, can considerably alter the quality of the releases from preimpoundment conditions. Figure 1 is a conceptualization of how reservoir processes may alter the water quality of inflows during the period of summer stratification. Note that in the releases summer water temperatures are depressed; particulate organic matter (POM), an important food source in unregulated streams, settles out within the reservoir and is not readily available in the tailwater; and nutrient concentrations increase. Similar graphs depicting changes in water quality resulting from impoundment could be presented for many other water quality constituents. Ward and Stanford (1979) and Walburg et al. (1981) can be consulted for more detailed information on how reservoirs impact tailwaters.

2.2.2.2 Physical and chemical changes in tailwaters caused by reservoir project operation are primarily determined by the volume and timing of releases, the chemical and biological conditions within the reservoir at the depth from which water is withdrawn, and the composition and shape of the stream channel and banks. The concentration of dissolved gases

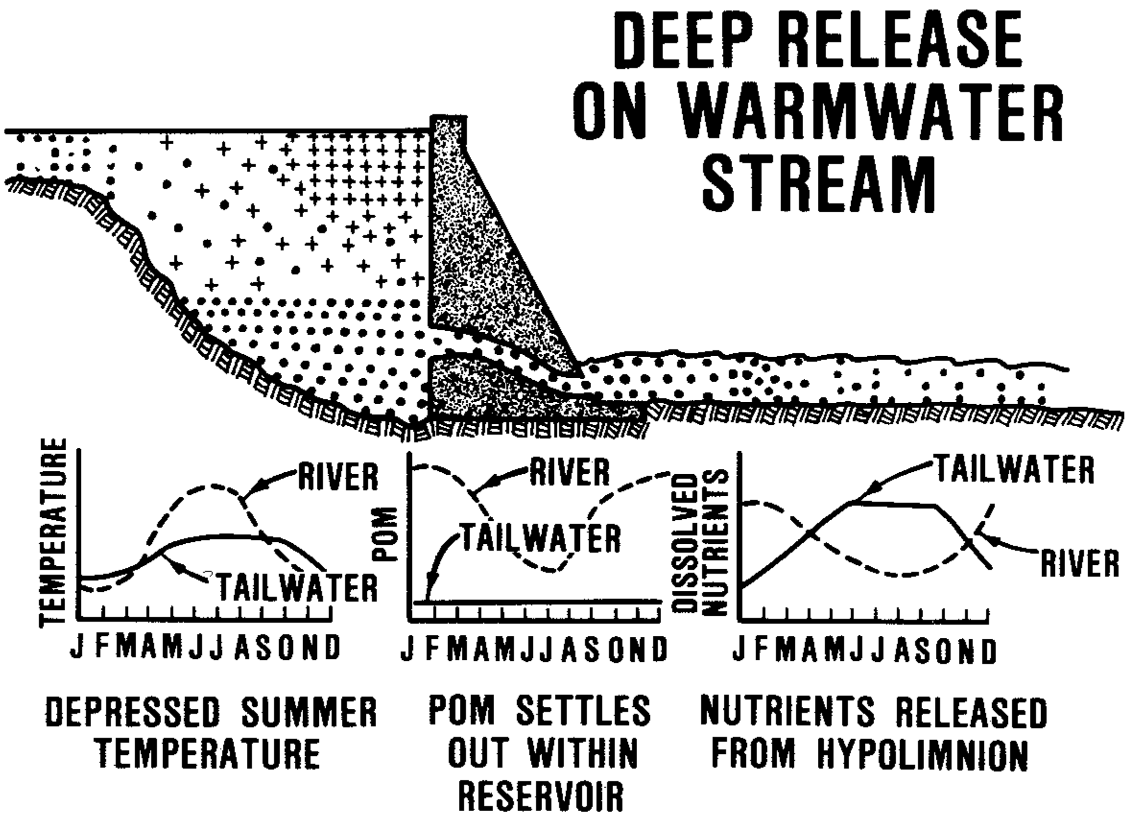

Figure 1. Conceptualized effects of a deep-release impoundment on on a formerly warmwater stream. Note that the inflows are well mixed but that as the water enters the stratified reservoir, certain constituents such as nutrients or metals (represented by dots), settle and concentrate in the hypolimnion of the reservoir. Other constituents, such as chlorophyll (represented by pluses), increase in concentration significantly above levels observed in the reservoir inflows. The net result of the impoundment is to considerably alter the quality of the releases compared to preimpoundment conditions. Additionally, the releases may travel downstream for a considerable distance before the quality of the releases again approaches preimpoundment conditions. The three graphs at the bottom of the figure contrast seasonal changes in certain key variables in an unregulated river and a tailwater

in water released from the reservoir is further altered during passage through the project outlet structure and stilling basin. The water quality of the releases can be further modified in the tailwater by ground-water inflow, runoff, tributary streams, biogeochemical processes (chemical transformation, photosynthesis, decomposition, etc.), and atmospheric influences.

2.2.2.3 The volume and timing of releases are determined by project purpose and runoff patterns in the watershed. Alterations in preimpoundment flows caused by peaking hydropower operation are described fully in the introduction to Part 3. Alterations in preimpoundment flows caused by flood control operation are discussed in the introduction to Part 4. Alterations caused by other types of reservoir operation are not discussed in this handbook.

2.2.2.4 The principal water quality parameters of concern downstream from a reservoir are temperature, POM, dissolved oxygen (DO), and metals (iron and manganese) and nutrients associated with reduced oxygen concentrations. Modifications in daily and seasonal temperatures caused by operation of a reservoir project are primarily determined by the depth of withdrawal; seasonal stratification patterns within the reservoir; and timing, frequency, and discharge rate of withdrawals. Relative temperature alterations caused by deep release and surface release are discussed in detail in section 2.4, "Relative Effects of Surface Versus Deep Release." In general, seasonal temperature changes are suppressed and delayed in tailwaters below nonstratified reservoirs because the time required to cool or warm a large volume of impounded water is significantly longer than the time required to cool or warm the smaller volume of water in an unregulated stream. Naturally occurring diurnal temperature fluctuations observed in unregulated streams are suppressed in tailwaters, especially near the reservoir outflow. However, summertime peaking power releases from a stratified, deep release project may cause extreme diel temperature fluctuations in the tailwater as cold-water releases to the tailwater warm during nongeneration periods and then are replaced by cold water from the reservoir hypolimnion during the onset of generation.

2.2.2.5 The modification of preimpoundment seasonal temperatures by a reservoir project may have a pronounced effect on aquatic biota since specific temperatures may terminate or initiate different life stages. For example, in unregulated streams and rivers, spawning by many species of fish is initiated, at least partially, by warmer, springtime water temperatures. Delayed warming downstream from a reservoir project will cause a delay or possible total postponement of spawning by some species of fish in a tailwater. Altered seasonal water temperatures also interfere with the normal progression of life-history stages of some species of aquatic insects. If the temperature modification is particularly severe, desirable aquatic insects (from a fisheries standpoint), such as mayflies and caddisflies (stoneflies are not usually abundant in tailwaters), may be replaced by groups such as black flies, midges, and oligochaetes.

2.2.2.6 Food webs differ between tailwaters and unregulated streams (for example, see Figure 2). In most large streams, the food chain is based primarily on allochthonous POM such as leaves, bark, and detritus washed in from the watershed. Many benthic organisms shred and ingest this material along with the associated bacteria and fungi. These benthic organisms are then eaten by many species of fish, either directly from the substrate or when the benthic organisms enter the "drift" (a phenomenon in which benthic organisms either voluntarily or accidentally leave the substrate and are swept downstream with the current to either reattach further downstream or to emerge). However, most allochthonous material settles out within the reservoir (if the hydraulic residence time is sufficiently long) and is largely unavailable in the tailwater ecosystem, although at high flows inundated streamsides provide detritus, terrestrial vegetation, and terrestrial invertebrates to the tailwater as in natural streams. The unavailability of allochthonous material, in combination with seasonal temperature alterations, causes a shift in the composition of the benthic macroinvertebrate communities in tailwaters (Figure 2). Note in Figure 2 that the density of mayflies (Ephemeroptera), a taxon in which many species shred and ingest

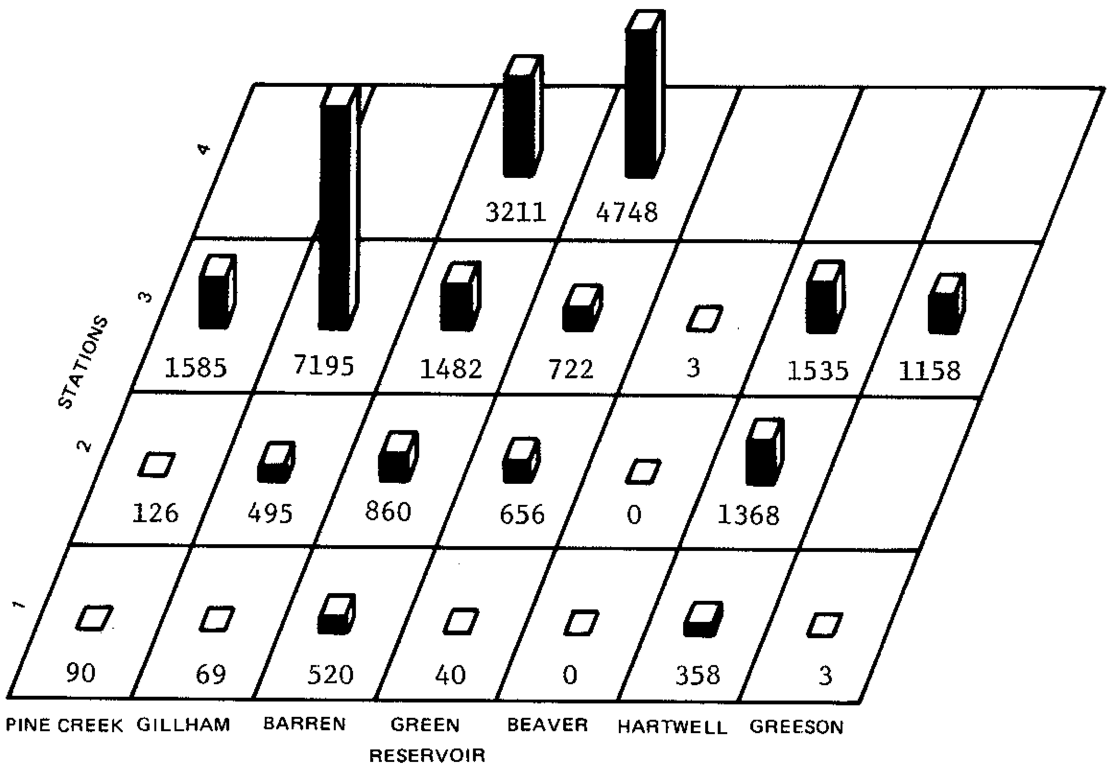

Figure 2. Example of changes in density (number/m^2) of Ephemeroptera (mayflies) at varying distances downstream from CE reservoir projects. Station 1 is located nearest the dam and station 3 is located farthest downstream. Station 4 is located upstream of the reservoir

allochthonous material, is depressed near the dam and increases with increasing distance downstream from the dam.

2.2.2.7 The type of food base and the general nature of the benthos in tailwaters are determined primarily by the release depth relative to reservoir stratification patterns. Surface-release projects (projects that discharge from the epilimnion) and reservoirs that are not stratified discharge phytoplankton, zooplankton, and prey fishes (smaller fishes that are eaten by sport fishes) into the tailwater. In many tailwaters downstream from surface-release projects, the benthos are dominated by filter-feeding organisms, such as net-building caddisflies, which are capable of utilizing material exported from the reservoir. Deep-release projects in which the reservoir is stratified and the hypolimnion is anaerobic typically discharge clear, nutrient-rich water that fosters the growth of periphyton; if the hypolimnion is aerobic, some phytoplankton, zooplankton, and fishes may be discharged into the tailwater. The benthos in these tailwaters are often dominated by grazers (organisms that scrape periphyton from rocks), such as some species of chironomids (midges), oligochaetes, amphipods, and isopods.

2.2.2.8 Patterns of abundance and distribution of fish are considerably altered in tailwaters from those observed in unregulated streams and rivers. Many tailwaters exhibit seasonal concentrations of fish to the extent that sport fisheries are developed and managed. A variety of site-specific factors cause fish to concentrate in the tailwaters of reservoir projects. Fish concentrate seasonally in tailwaters because dams may block upstream migration. At other times, some species of piscivorous (fish-eating) fish may congregate in the tailwater when prey fish are discharged from the reservoir. Additionally, fish appear attracted to tailwaters in the winter because the reservoir releases are often warmer than unregulated rivers. A major source of increased abundance of fish in tailwaters, particularly in the tailwaters of nonhydropower, flood control projects, appears to be movement of fish from the reservoir into the tailwater. That is, reservoirs serve as a source of recruitment for many of the fish found in the tailwater in addition to natural reproduction in the tailwater. Fish passage through the project or over the spillway can occur sporadically at any time of the year (e.g., summertime movement of striped bass through the turbines or springtime movement of walleye as they congregate to spawn on the riprap on the face of a dam), but is generally most common during periods of destratification, particularly in the fall and winter when fish move into deeper water in the reservoir (and consequently nearer to the vicinity of the intakes) and the discharge rate is increased for flood control operation. Natural reproduction does not appear to be an important source of recruitment in some formerly warmwater streams downstream from deep-release projects because coldwater releases interfere with successful spawning.

2.2.2.9 Water quality modifications in the tailwater from preimpoundment conditions are determined primarily by biogeochemical and physical processes within the reservoir at the depth from which water is withdrawn. Surface-release projects generally do not release water of poor quality except, perhaps, immediately following reservoir destratification. Deep-release projects may discharge flows of poor quality if the reservoir is thermally stratified and the hypolimnion is anaerobic. However, considerable improvement in the quality of releases may occur through reaeration as water passes through the outlet works of flood control projects. One of the limnology references cited in Part 1 should be consulted for further information on limnological processes of importance in understanding relationships between tailwater water quality and reservoir water quality.

2.2.2.10 The physical habitat of the tailwater is also altered as a consequence of reservoir operation. In an unregulated stream, the composition of the channel bed reflects the dynamic equilibrium between deposition and transport as sediment moves progressively downstream in the system. However, the presence of a reservoir disrupts the downstream movement of sediment by capturing most suspended sediments and bed load. The changes caused in the tailwater physical habitat by alterations in sediment transport are discussed in detail under the topics of "Scour and Armoring" (section 2.7), "Sedimentation" (section 2.8), "Impacts of Highly Fluctuating Flows" (section 3.5).

2.2.2.11 References

Walburg, C. H., Novotny, J. F., Jacobs, K. E., Swink, W. D., Campbell, T. M., Nestler, J. M., and Saul, G. E. 1981. "Effects of Reservoir Releases on Tailwater Ecology: A Literature Review," Technical Report E-81-12, prepared by US Department of the Interior for US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Ward, J. V., and Stanford, J. A., eds. 1979. The Ecology of Regulated Streams, Plenum Press, New York.

2.3 Useful Simulation Techniques for Reservoir Release Applications

2.3.1 Topic Description

2.3.1.1 Environmental quality downstream of CE reservoir projects is often determined by interrelationships among water quality conditions within the reservoir, design and operation of the dam, and localized meteorological and geological conditions in the tailwater. Because of these complex interrelationships, efficient identification of design or operational alternatives that are least detrimental to the tailwater ecosystem often cannot be based on subjective considerations alone, but require application of a quantitative, predictive method. Generally, this will involve use of a numerical simulation code for predicting impacts of reservoir releases on water quality conditions within the tailwater or farther downstream. Typical water quality problems addressed by such codes include temperature, high concentrations of heavy metals or reduced chemical species, presence of noxious gases, and low DO concentrations.

2.3.1.2 A variety of useful numerical simulation codes are available, differing in temporal and spatial resolution; in the assumptions and limitations inherent in model formulations; in the specific physical, chemical, and biological processes included in the code; and in the numerical algorithms employed to describe those processes that are included. Thus, it may not be immediately clear which code is most appropriate for analyzing a specific tailwater problem.

2.3.2 Discussion

2.3.2.1 Numerical codes useful for predicting impacts of reservoir releases on water quality conditions in the tailwater can generally be divided into two broad categories: codes useful for far-field problems and codes useful for near-field problems. Far-field problems generally have to do with impacts of reservoir releases far downstream of the dam structure (e.g., measured in units of miles). Far-field studies involve the downstream routing of water quality constituents contained in reservoir releases as well as consideration of in-stream changes in constituent concentrations due to physical, chemical, and biological processes in the river as a function of distance below the dam. Such problems can typically be addressed with riverine water quality codes. The types of available riverine codes are briefly described later in this section.

2.3.2.2 Near-field problems have to do with water quality conditions in the tailwater just below the dam as influenced by reservoir releases. Two different types of codes are available for examining such problems: one relies on access to measured profiles of the water quality constituents of interest in the reservoir in the vicinity of the outlet structure, and the other requires predictions of both in-pool and release water quality with a single code. The code SELECT (Bohan and Grace 1973) can be used to predict the quality of reservoir releases in situations where vertical profiles of concentrations of reservoir water have been directly measured for representative time periods critical to tailwater water quality considerations. SELECT calculates the amount of water released from each of a series of discrete depth strata as a function of total discharge using data on the number, type, size, and location of outlet ports relative to existing thermal stratification within the reservoir. Together with measured data on concentration profiles for specific water quality constituents (temperature must be included), SELECT will allow prediction of the final, volume-weighted concentration of each constituent in the reservoir discharge.

2.3.2.3 If vertical profiles of water quality constituents do not exist (for example, if future conditions are being predicted), a separate code must be employed to predict water quality conditions within the reservoir before SELECT can be used to predict water quality of the releases. Both one- and two-dimensional reservoir water quality codes are available. One-dimensional codes allow prediction of changes over time in water quality constituent concentrations along the vertical reservoir axis; they most accurately describe conditions in the deep pool near the dam. Two-dimensional codes allow prediction of temporal dynamics of water quality conditions along both vertical and longitudinal reservoir axes. Since release water quality is a near-field problem, consideration of the longitudinal dimension is typically unnecessary, so that only one-dimensional codes are usually required to assess water quality conditions in reservoir releases and in the immediate tailwater environment.

2.3.2.4 CE-QUAL-R1, developed under the CE Environmental and Water Quality Operational Studies Program, is perhaps the most versatile and useful of the many one-dimensional reservoir water quality codes available for predicting water quality conditions in the deep pool near the dam and the reservoir releases. This code includes specific consideration of a wide variety of hydrophysical, chemical, and biological processes that affect both in-pool and release water quality and allows the user to simulate the dynamics of up to 36 water quality variables. Water quality variables included in the code that are often important in tailwater studies are: algal nutrients (i.e., nitrogen and phosphorus); oxidized and reduced forms of iron, manganese, and sulfur; DO; suspended and total dissolved solids; dissolved and particulate organic matter; coliform bacteria; and temperature. The code also includes a number of features for enhanced usefulness, including an advanced graphics package for plotting simulation results and Monte Carlo capabilities for examining effects of uncertainty on code predictions.

2.3.2.5 If the only concern is with the temperature of reservoir releases, then CE-THERM-R1, a submodel of CE-QUAL-R1, may be employed. This code includes only those processes that specifically impact in-pool and release water temperature. WESTEX is a similar, one-dimensional reservoir temperature code useful for reservoir release problems. The major difference between CE-THERM-R1 and WESTEX is that the former is a variable layer code, while the latter is a fixed layer code. All three codes mentioned here include SELECT and have the capability for modeling pumped-storage projects. Both CE-QUAL-R1 and CE-THERM-R1 are thoroughly documented (Environmental Laboratory 1982, new update should be available in 1986).

2.3.2.6 A number of other one-dimensional reservoir water quality codes are also available and are useful for examining reservoir release problems (e.g., the reservoir portion of WQRRS, LAKECO, and EPARES). No attempt will be made here to differentiate among the various vailable codes. Although all of these codes have many features in common, they generally do not include some of the more useful features contained in CE-QUAL-R1 and CE-THERM-R1. Among the shortcomings of some of these codes are the following: failure to include state-of-the-art descriptions of reservoir hydrodynamics appropriate for the one-dimensional reservoir representation; simulation of a smaller number of water quality constituents; lack of graphics capabilities as well as other user-friendly features; and reduced flexibility in the specification of reservoir morphometry, outlet configuration, or other reservoir-specific operational features.

2.3.2.7 Reservoir water quality simulation can also be used with optimization techniques for developing both the design (or modification) and operation of reservoir projects. One technique can be used to optimize the depth, size, and number of intake ports needed to meet a range of downstream flow and water quality (usually temperature) requirements under a particular set of hydrologic conditions, meteorologic conditions, and hydraulic constraints (Dortch and Holland 1984). Additionally, optimization techniques can be used to develop operational guidance for reservoir projects that have selective withdrawal capability (Fontane, Labadie, and Loftis 1982). For this application, operation plans can be developed that have a higher probability of meeting downstream water quality targets over time. For example, simulation/optimization could be used to develop an operation plan for a flood control project (nonhydropower) that supports a tailwater trout fishery. This operation plan would be designed to maximize the probability that cold water could be supplied to the tailwater through the entire period of warm weather.

2.3.2.8 Far-field reservoir release problems can be addressed using riverine water quality codes. Riverine water quality codes are generally classified according to the number of dimensions considered, the level of detail of the simulations, and the types of conditions (whether time-varying or steady-state) that can be simulated. Ordinarily, most downstream water quality problems associated with reservoir project operation can be addressed using a one-dimensional code since mixing caused by turbulent flow and passage of the flows over shoal and riffle areas generally prevents either vertical or cross-channel (lateral) differences in water quality.

2.3.2.9 One-dimensional water quality codes range in complexity from relatively simple "desk top" codes used to simulate steady-state (meteorological conditions do not change over the time period covered by the analysis), to steady flow (discharge or flow do not change over the time period of the analysis), to dynamic riverine codes that can be used to simulate conditions in which all variables are time-varying. The cost, effort, and data requirements vary directly with the complexity of the code.

2.3.2.10 The following riverine water quality codes are representative of the many formulations that are available to route water quality downstream of dams. Modifications of the Streeter-Phelps code are generally the simplest, most commonly used riverine water quality codes. A code of this type, such as the US Geological Survey version (Bauer, Jennings, and Miller 1979), is useful for simulating some water quality parameters under steady-state, uniform-flow conditions. Another widely used water quality code is QUAL II. This code is recommended for use by the Environmental Protection Agency because of its effectiveness, ease of use, documentation, and general acceptance by water quality modelers. The QUAL II code can predict time-varying changes in temperature and water quality constituents such as DO, chlorophyll-a, and nutrients in response to dynamic meteorological conditions. However, QUAL II is limited to steady-flow applications.

2.3.2.11 Codes are available that are not limited to steady-state flow conditions. CE-QUAL-RIV1 (Bedford, Sykes, and Libicki 1985) is a riverine water quality code that has been successfully applied to predict water quality conditions under dynamic flow conditions common downstream of peaking hydropower projects. WQRRS can also be used to simulate time-varying stage, flow, and water quality. This code is documented and supported by the Hydrologic Engineering Center. Refer to McCutcheon (1983) and Ambrose et al. (1981) for a detailed description and evaluation of commonly used one-dimensional riverine water quality codes.

2.3.3 Recommendations

Although water quality codes are extremely useful for examining reservoir release problems, they are complex tools requiring multidisciplinary expertise in biology, chemistry, physics, and mathematics; prior experience or training in numerical modeling; and site-specific data and information. Thus, they should be used only after proper training or in collaboration with WES personnel or other qualified individuals.

2.3.4 References

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2.4 Relative Effects of Surface Versus Deep Release

2.4.1 Topic Description

Many reservoirs stratify chemically and thermally during some portions of the year. Thus, chemical and physical conditions in the reservoir may vary considerably from near the surface to the bottom. Dams may discharge water from near the surface or from deep in the reservoir or, in some cases, a blend of water may be released from various depths if the project has a selective withdrawal capability. The depth from which water is released from a stratified reservoir can be one of the most important factors determining the composition and abundance of tailwater biota.

2.4.2 Discussion

2.4.2.1 Release depth(s), physical and chemical conditions in the reservoir at the depth from which water will be withdrawn, and preimpoundment classification of the downstream reaches (as a warmwater, coolwater, or coldwater stream) are of primary importance in determining the effects of release depth on tailwater biota. For clarity and brevity of discussion, only the effects of surface or deep release will be discussed. The effects of selective withdrawal will not be discussed because many different combinations of release water are possible. Also, this discussion will be limited to reservoirs that stratify since there is little difference between surface and deep release for projects that do not stratify.

2.4.2.2 The relative effects of surface release versus deep release on a stream or river are determined by the altitude and latitude of the project and the physical and chemical conditions within the reservoir at the depth of withdrawal. Altitude and latitude of the project will, in the majority of cases, determine the preimpoundment classification of the affected river reaches as coolwater, coldwater, or warmwater streams. The aquatic biota found in each of these different systems vary considerably in their water quality tolerances and requirements.

2.4.2.3 Although algal blooms in the reservoir have, on occasion, resulted in short-term toxic effects in the tailwater, the effects of surface release on a warmwater stream are generally not detrimental unless gas supersaturation occurs. Gas supersaturation occurs when releases with entrained gas (air) plunge into deep pools in the tailwater. Hydrostatic pressure in the deep pool forces the entrained gas into solution. The gas gradually comes out of solution as the water proceeds through the shallower reaches of the tailwater. The gas may come out of solution within the bodies of aquatic organisms (caisson (gas bubble) disease, "the bends") causing embolisms and, perhaps, death. Fast and Holquist (1982) and Transactions of the American Fisheries Society (1980) describe gas supersaturation in tailwaters and provide suggestions to alleviate this condition.

2.4.2.4 The effects of altered water temperature and quality on tailwater biota caused by surface releases into a formerly warmwater stream are generally not serious. In terms of water quality only, releases from the surface of a project are generally similar to the outflow of a natural lake. The major tailwater temperature alterations (delayed spring warming, increased summer water temperature, delayed fall cooling, and increased winter water temperatures) have not been documented to harm tailwater aquatic biota. Poor release water quality is generally not a problem except immediately subsequent to reservoir mixing if the reservoir is chemically stratified. Consequently, many of the fish species found in the river before the project was built may still be found once the project is in place because conditions in the tailwater fall within the tolerance limits of many warmwater organisms.

2.4.2.5 The benthic community in a formerly warmwater stream downstream from a surface-release project will exhibit a shift in composition. The tailwater often becomes dominated by filter-feeders that appear to ingest phytoplankton and zooplankton discharged from the project. Species that feed on allochthonous material washed in from the watershed decline in numbers since much of this material will settle in the reservoir and not be available in the tailwater.

2.4.2.6 In an unregulated stream or river, the major sources of recruitment to a fish community are natural reproduction and instream movement. However, in a warmwater tailwater, natural reproduction of fish will be supplemented by passage of fish from the reservoir into the tailwater. Thus, the fish community in a tailwater downstream from a surface-release project may exhibit a shift in composition as reservoir fish recruit into the tailwater.

2.4.2.7 Additional sources of recruitment of fish into the tailwater fishery may be of site specific or seasonal importance. The discharge of forage fish from the reservoir may attract predatory fish into the tailwater. Fish may also concentrate in the tailwater because of blockage of upstream spawning migrations and because release temperatures in winter may be warmer than water temperatures farther downstream.

2.4.2.8 Changes in the depth of release may occur as a consequence of flood control operation at a nonhydropower project. The project may discharge water from the upper ports under low-flow conditions, but discharge water from a deep floodgate during flood control operation. Ordinarily, the switch from surface release to deep release is not detrimental to the tailwater ecosystem since high flows are released in the spring prior to reservoir stratification and in the fall near the period of destratification. Thus, the chemical and temperature changes experienced by the tailwater may not be excessive. However, a switch from a surface gate to the deep gate when the reservoir is strongly stratified may be detrimental to tailwater aquatic biota due to thermal or chemical shock.

2.4.2.9 The effects of deep release on a coldwater stream appear to be determined primarily by water quality, since the release temperatures generally fall within the tolerances of coldwater aquatic organisms, although in some instances release temperatures may be sufficiently cold to slow the growth rates of some organisms. Seasonal water quality problems may occur downstream from deep-release projects if the hypolimnion becomes anaerobic.

2.4.2.10 The effects of deep release from thermally stratified reservoirs on warmwater streams and rivers are determined by the water quality at the depth of withdrawal and the extent of alteration of pre-impoundment temperatures. The temperature effects and often the water quality alterations caused by deep release on formerly warmwater streams are usually extensive. Generally, mean and maximum water temperatures are lowered in the tailwater and the transport of particulate organic matter is disrupted. Although some warmwater organisms may be able to survive in the tailwater, they are unable to reproduce. Consequently, the abundances of many species of warmwater fishes may be reduced (Figure 3), and many common stream insect groups such as Ephemeroptera

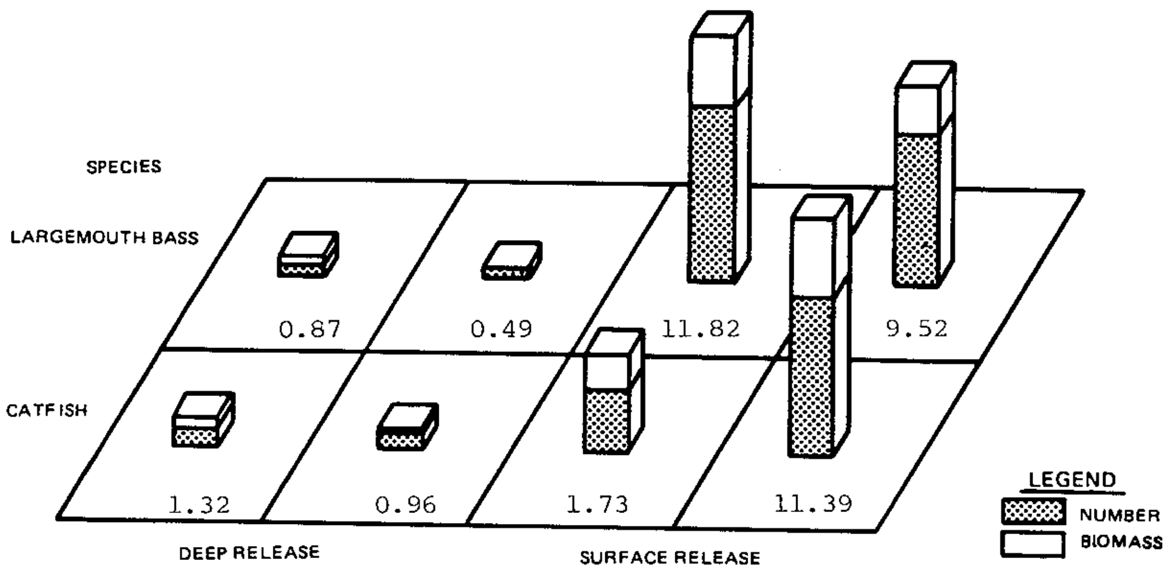

Figure 3. Mean biomass (kilograms per hour of electroshocking) and mean number (number per hour of electroshocking) of warmwater fish downstream from surface-release (Gillham Lake, Ark., and Pine Creek Lake, Okla.) and deep-release (Barren River Lake, Ky., and Green River Lake, Ky.) projects on formerly warmwater streams

(mayflies), Trichoptera (caddisflies), and Plecoptera (stoneflies) are unable to colonize these areas. The benthic community is limited to species that do not appear to require a temperature stimulus for the normal progression of life-history stages (amphipods, isopods, oligochaetes, and some dipterans). Low DO concentrations and high concentrations of reduced compounds, such as iron and manganese, in the discharges during periods of stratification in the reservoir may stress aquatic organisms in the tailwater and, in some systems, may account for the low diversity and biomass of tailwater biota in the summer and fall.

2.4.2.11 Deep releases into formerly warmwater streams may substantially alter the base of the food chain in the tailwater. Rather than being based on allochthonous material such as leaves, bark, and detritus, the food web may be based on periphyton growing in the tailwater. The clear, nutrient-rich deep releases foster the luxuriant growth of periphyton which, in turn, provide a food source for grazing macroinvertebrates such as chironomids, oligochaetes, amphipods, isopods, and some mayflies.

2.4.2.12 Species composition and abundance of fish in the tailwater are partly determined by project operation. In tailwaters of deep-release flood control (nonhydropower) projects that are drawn down extensively, the fish community may be dominated by fishes from the reservoir that move through the reservoir outlet works into the tailwater or fish that seasonally concentrate below the dam during upstream migration. Most warmwater riverine fishes are poorly represented in coldwater tailwaters (see Figure 3). In general, their reproduction in the tailwater is impaired because reduced water temperatures interfere with spawning. Tailwaters downstream from deep-release peaking hydropower projects are characterized by low biomass and diversity of fish since fish passage through the outlet works is reduced and thermal and chemical conditions in the tailwater generally inhibit recruitment through natural reproduction. These tailwaters may be suitable for the establishment of a put-and-take trout fishery if the reservoir has sufficient storage of cold water of the appropriate quality (DO above 5.0 ppm and reduced levels of metals) to maintain the trout fishery through the summer months.

2.4.2.13 Deep-release projects (particularly nonhydropower, flood control projects) that support a put-and-take trout fishery on formerly warmwater streams may experience a shortage of cold hypolimnetic water during the late summer and early fall in some years. Thus, the trout fishery cannot be maintained throughout the year because increased water temperatures during the summer are detrimental to trout. Consequently, the tailwater environment becomes too warm for coldwater organisms and too cold for warmwater organisms since the coldwater temperatures earlier in the summer prevent natural reproduction by warmwater biota in the tailwater.

2.4.2.14 The effects of surface releases warm enough to convert a formerly coldwater stream to a warmwater stream are not well documented. There is some evidence that increased water temperatures in coldwater streams can favor warmwater organisms and allow them to outcompete coldwater organisms because the coldwater organisms may become less active as water temperatures increase. As a result, the growth rate of coldwater organisms may decrease or the coldwater organisms may migrate out of the tailwater. Coldwater organisms may also become more susceptible to disease as water temperatures increase. In addition to these specific effects of warmwater release on coldwater organisms, other generalized effects are related to alterations in the yearly temperature cycle (delay in seasonal warming and cooling that can affect reproduction), alterations in the downstream transport of allochthonous material, and changes to preimpoundment water quality.

2.4.3 Recommendations

2.4.3.1 Within the framework of authorizing legislation, the CE designs and operates reservoir projects according to recommendations made by State and Federal conservation agencies. Thus, the decision to create a warmwater or coldwater fishery downstream from a CE project is made jointly by the State and the CE District. However, based on nationwide experience, the following recommendations can be made that consistently produce quality downstream habitat for tailwater biota. These recommendations should be considered during discussions with the State in which project design and operation are determined. Ideally, selective withdrawal capability should be considered for CE reservoir projects so that project operation can be more easily modified to reflect changing attitudes by the State and local communities.

2.4.3.2 The nature of the recommendations are determined by project purpose. Flood control (nonhydropower) projects should release water of the same approximate temperature as preimpoundment conditions. Warmwater streams should receive releases that warm significantly in the summer, and coldwater streams should receive water consistently below a temperature of 20° C. Flood releases should be of the same temperature as low-flow releases. Optimization techniques can be used to determine release volumes and depths for projects on formerly warmwater streams so that adequate storage of cold water is maintained to support downstream put-and-take trout fisheries through the summer months. Deviations from this scheme may considerably disrupt the tailwater ecosystem.

2.4.3.3 Peaking hydropower projects should also release water at temperatures approximating preimpoundment water temperatures in the stream. Peaking hydropower projects on warmwater streams and rivers should release warm water and projects on coldwater rivers and streams should release cold water. However, a deep-release project on a warmwater stream or river may support a quality put-and-take or put-grow-and-take trout fishery if poor water quality of the releases is not a problem.

2.4.3.4 Detailed water quality studies should be considered for reservoir projects in the planning stages to provide final guidance on the design and operation of reservoir outlet structures. These studies are necessary to determine both stratification patterns within the reservoir and water quality of the releases. Results of these studies should be coordinated with State and Federal conservation agencies to select the most viable design and operation alternatives. The section "Useful Simulation Techniques for Reservoir Release Applications" (section 2.3) contains further guidance on water quality simulation codes. Also, the goal of reservoir water quality simulation should be to optimize water quality within both the reservoir pool and the tailwater because attempts to alter the water quality of the releases may also result in water quality changes in the reservoir pool.

2.4.4 References

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Transactions of the American Fisheries Society. 1980. Vol 109.

2.5 Conduit Inspection

2.5.1 Topic Description

Many reservoirs use a conduit to convey releases from the reservoir into the tailwater. Conduits experience wear over time and consequently must be dewatered at regular intervals for inspection and maintenance. At this time, the tailwater ecosystem receives no discharges from the dam except seepage, and portions of the tailwater may be completely dewatered. Dewatering of the tailwater may substantially impact downstream aquatic biota.

2.5.2 Discussion

2.5.2.1 The effect of a conduit inspection on the tailwater ecosystem is determined by project purpose, season, release depth, and shape of the river channel.

2.5.2.2 A conduit inspection downstream from a peaking hydropower project that discharges no minimum low flow other than seepage will have impacts similar to those of nongeneration except that conduit inspections may be of longer duration. A conduit inspection downstream from a flood control project may have a more detrimental effect since the seepage flow may be substantially less than the minimum low-flow release from the project. Consequently, benthos and fish may be stranded and desiccate or aquatic biota may be crowded into a few remaining pools in the tailwater where they may be exposed to poor water quality or increased predation.

2.5.2.3 Effects of a conduit inspection are also determined by the shape of the channel in the tailwater. Channels characterized by deep pools connected by riffle areas will be less susceptible to effects of dewatering since ample habitat will be provided by pools although some stranding of benthos may occur in riffle areas. Channels characterized by runs, or long sections of river without pools and riffles, are more sensitive to effects of conduit inspection since little habitat will remain during dewatering.

2.5.2.4 Seasonal meteorological conditions can have a substantial effect on the final impacts of a conduit inspection. Summer insolation during a prolonged conduit inspection could cause considerable warming of tailwaters that support a coolwater or a coldwater fishery with the resultant death of aquatic organisms. The initial release wave from a deep-release project could result in thermal or chemical shock to aquatic organisms as the water temperature and quality change substantially over short time periods. Conduit inspections conducted in the wintertime may also stress downstream organisms. Exposed organisms may suffer exposure and freezing as the tailwater is dewatered.

2.5.3 Recommendations

Conduit inspections do not ordinarily disrupt the tailwater ecosystem. However, the following recommendations will ensure that effects of conduit inspections remain minimal:

a. Conduit inspections should be generally scheduled in the fall (only if no fish activities occur downstream of the dam in the fall) to avoid either summer heating or winter freezing of stranded or crowded aquatic organisms or interference with spring spawning.

b. Inspections should be completed as quickly as possible.

c. Efforts should be made to supply the tailwater with some flows, if possible, by siphoning or pumping water over the dam or by some other means, particularly for flood control projects or for hydropower projects that release a sustained minimum low flow other than seepage.

d. Flow into the tailwater should be increased gradually after the completion of the conduit inspection if the temperature or water quality of the releases differs from conditions in the tailwater.

2.6 Selection of a Water Quality Objective When All Downstream Water Quality Targets Cannot Be Met

2.6.1 Topic Description

Reservoirs are often operated to meet downstream objectives for more than one water quality constituent. In some cases, the reservoir will be unable to achieve all downstream water quality objectives. For example, the releases from a project operated to support a tailwater trout fishery should not exceed a certain maximum temperature and must equal or exceed a certain minimum DO. However, under some conditions (late summer stratification), the project cannot meet both objectives. Although water in the hypolimnion of the reservoir is sufficiently cool to meet the downstream objective, the hypolimnion may be devoid of oxygen. Concomitantly, the surface waters have an acceptable DO concentration but may be too warm. A decision must then be made to meet the DO objective and violate the temperature objective, to meet the temperature objective and violate the DO objective, or to compromise both objectives by releasing a blend of water that meets neither objective.

2.6.2 Discussion

Currently, there is insufficient information to address this problem because the degree to which site-specific, season-specific, and species-specific factors interact is not completely known. Additionally, the concentration of other water quality constituents that may be detrimental to aquatic organisms may be correlated to one of the water quality objectives. For example, at some sites high concentrations of iron and manganese may be associated with reduced oxygen concentrations.

2.6.3 Recommendations

2.6.3.1 No recommendations can be provided at this time to resolve this problem. However, in most cases, this problem can be avoided in one of two ways. First, the project should be operated under a management plan (developed in cooperation with State and Federal natural resource agencies) that considers the capabilities of the reservoir project. For example, establishment of a put-and-take trout fishery on a warmwater stream downstream from a small flood control project should be avoided since the project may lack sufficient predictable storage and operational flexibility to consistently meet downstream temperature and other water quality objectives. Instead, this project should be operated to support a warmwater fishery in the tailwater, thereby avoiding the problem.

2.6.3.2 In some cases, switching from deep release to surface release may not be feasible because of the design of the outlet works, because State officials and local residents may be unwilling to give up a tailwater trout fishery, or because of historical commitments. In this case, simulation techniques are available to formulate operational guidelines to increase the probability that both water quality objectives can be met. One- or two-dimensional reservoir water quality codes can be used to simulate average and worst-case scenarios under different inflows and various discharges and discharge depths. The effects of these releases can then be evaluated since the environmental quality requirements of many aquatic organisms (particularly sport fish) are currently documented or can be determined with additional study. The results of the simulation can then be evaluated, in light of the environmental quality requirements of different organisms, to devise a management plan that allows the project to meet authorized purposes and also falls within the capabilities of the project. The reader should refer to the section "Useful Simulation Techniques for Reservoir Release Applications," section 2.3, for guidance on application of numerical simulation techniques to solve reservoir release water quality problems.

2.6.3.3 Optimization techniques can be used to determine the combination of gates and discharges that is needed to maximize the likelihood that downstream water quality objectives can be met throughout the year or during critical seasons. Optimization techniques should be used to formulate operational procedures for those projects that are unable to consistently meet single or multiple downstream water quality objectives. Section 2.3, "Useful Simulation Techniques for Reservoir Release Applications," has further information on this topic.

2.6.3.4 If application of numerical simulation and optimization techniques indicates that no operation plan will allow the project to meet downstream water quality objectives under most anticipated operating conditions, then the objectives must be changed, installing aeration capability must be considered, or the outlet works should be modified.

2.7 Scour and Armoring

2.7.1 Topic Description

Most reservoir projects are efficient sediment traps. The sediment load of the inflows settles out in the upper reaches of the reservoir as the turbulence and water velocity of the inflows decrease. Consequently, reservoir releases usually contain little or no suspended sediment. Disruption of downstream sediment transport by the reservoir plus scouring or sluicing out of finer particles in the immediate tailwater by release of water from the reservoir result in a shift in composition of the channel bed. As finer materials are swept downstream, the channel degrades (decreases in elevation) and becomes "armored" with a layer of cobble and rubble too heavy to be swept away by the current; the channel may degrade down to bedrock if bedrock is near the surface.

2.7.2 Discussion

2.7.2.1 The severity of the downstream effects of armoring is determined by the composition of the tailwater channel, the volume of the discharges relative to the channel capacity, and the purpose of the project. In general, effects of armoring are not significant in those tailwaters having a channel composed of coarse gravel and cobble. In fact, armoring may enhance habitat quality of the tailwater ecosystem over preimpoundment conditions if sand and fines are removed to reduce embeddedness of larger substrate particles. Positive effects of armoring include increasing the amount of interstitial habitat available for benthos and small bottom-dwelling fish, providing a stable substrate for periphyton, and reducing smothering effects of sediment on fish nests and benthos.

2.7.2.2 Effects of armoring are more substantial in tailwaters that degrade to bedrock and boulders. This type of channel provides little interstitial habitat for benthos or fish, and nesting sites will be unavailable for fish, although fractured bedrock may provide some habitat for benthos and fish.

2.7.2.3 The rate at which armoring occurs, the severity of armoring, and the distance that armoring extends downstream are related to discharge patterns of reservoir projects which, in turn, are determined by project purpose. Entrainment of sediment and movement of bed load are complex phenomena but generally related exponentially to water velocity. That is, a small increase in water velocity will result in a greater increase in sediment transport. Thus, for a constant total discharge, a nonfluctuating release (as typified by a flood control project) will result in a slower rate of armoring than a fluctuating release (as typified by peaking hydropower projects) in which the high flow is greater than the nonfluctuating releases. Additionally, effects of armoring will extend farther downstream in tailwaters receiving fluctuating flows.

2.7.3 Recommendations

2.7.3.1 Armoring is one of the most fundamental impacts associated with reservoir projects and cannot be totally eliminated. Efforts to minimize armoring are not recommended without further site-specific investigations to determine the actual effects of this process because, in some cases, environmental effects of armoring may not be severe or may even enhance tailwater habitat for aquatic organisms. Caution should be exercised even if further studies indicate that the effects of armoring may be severe. Severe armoring is usually associated with peaking hydropower operation and consequently represents one of a syndrome of environmental effects. (Refer to Part 3, "Peaking Hydropower Topics," for further information.) Reducing armoring may have little beneficial effect if observed detrimental downstream effects are actually related to insufficient low flows, altered seasonal water temperature regimes, poor water quality, or some other effect usually associated with peaking hydropower operation.

2.7.3.2 The rate of armoring can be reduced by decreasing the velocity of discharges if detailed studies indicate that armoring is resulting in substantial negative effects on tailwater organisms. However, the decrease in current velocity necessary to reduce the rate of armoring can be determined only with great difficulty.

2.8 Sedimentation

2.8.1 Topic Description

In an unregulated river, sediments are eroded from the watershed into the stream channel. River currents transport the eroded sediments downstream either as sediment load or bed load. Thus, at any point in a river, the composition of the channel bed represents a dynamic equilibrium between the opposing processes of sediment transport and deposition. An impoundment changes tailwater sediment composition from preimpoundment conditions both because the downstream transport of material is interrupted and because the downstream flow regime is altered.

2.8.2 Discussion

2.8.2.1 Patterns in the tailwater distribution and sorting of sediments are determined by initial composition of the channel substrate, release patterns (project purpose), and sediment load of downstream tributaries. Highly fluctuating water levels and passage of a highly turbulent "power wave" associated with start-up of generation generally erode the river channel and riverbanks near the project and redeposit this material further downstream. Environmental consequences of downstream deposition of sediment have not been documented but are probably similar to sedimentation of fines in most aquatic ecosystems. Fines reduce interstitial habitat by filling spaces within and between rocks in riffle areas and "smother" some benthic macroinvertebrates and fish spawning and nesting areas.

2.8.2.2 Sediment redistribution is less severe downstream from flood control impoundments because nonfluctuating flows transport less sediment (see paragraph 2.7.2 of "Scour and Armoring" for more detailed information). Additionally, since the peaks of the preimpoundment yearly hydrograph are eliminated, the flows with the greatest capacity to transport sediment out of the tailwater are also reduced. Encroachment of the channel by riparian vegetation may also result since the peak yearly flows that maintain the channel are reduced.

2.8.2.3 In most cases, alteration of sedimentation patterns downstream from flood control projects has minimal environmental consequences, except when an unregulated tributary joins the tailwater. Occasionally, a sedimentation problem will develop at the confluence of the two channels since the flows in the tailwater are of insufficient velocity to transport the sediment deposited by the tributary.

2.8.3 Recommendations

Effects of sedimentation downstream from peaking hydropower projects caused by redeposition of sediments from near the project have not been documented to cause downstream environmental quality problems. Consequently, actions designed to minimize or ameliorate this effect are unnecessary. Minor sedimentation problems in tailwaters of nonhydropower, flood control projects can often be alleviated by releasing short-term "flushing flows" (high flows of short duration) into the tailwater to remove downstream sediment accumulations that may be having a negative effect on downstream biota. Chronic or major sedimentation problems in a tailwater may require the assistance of the WES Hydraulics Laboratory or a hydraulic engineer specializing in sediment transport because of the highly complex interrelationships among discharge, channel change, sedimentation, and channel and bank erosion.

2.9 Target Species Selection

2.9.1 Topic Description

2.9.1.1 Reservoir projects may be operated to meet the habitat requirements of a particular target species in the tailwater. Although responsibility for selecting downstream target species usually lies with a State or Federal fish and wildlife agency, CE personnel must also be aware of the principles involved in selection of a target species because of the potential impact that selection may have on the design and operation of a reservoir project. For example, a reservoir project could be operated to meet water quality and temperature requirements of rainbow trout in the tailwater; that is, the project could support a coldwater fishery in the tailwater. For this particular species, the releases from the dam should not exceed the maximum tolerance temperature nor should the DO concentration fall below the minimum tolerance level.

2.9.1.2 In some instances, constraints imposed by project design and operation will unavoidably cause project releases to violate conditions necessary to maintain a particular target species. Thus, selection of an inappropriate target species may compromise authorized project purposes; result in expensive, unsuccessful efforts to meet the requirements of the target species; or result in the unavoidable disruption of downstream habitat for the target species.

2.9.2 Discussion

2.9.2.1 Several different criteria can be used to select target species in tailwaters. First, a target species that is of great public interest or economic value can be selected. For example, a sport fish (such as smallmouth bass or rainbow trout) or a commercial fish (such as buffalo or carp) would be a suitable target species using this criterion. Alternatively, an indicator species can be selected that functions much like a barometer for the rest of the aquatic community. In this case, the indicator species would have environmental requirements reflective of the health of the aquatic community in general. For example, smallmouth bass would be an excellent target species for a coolwater stream. Conditions in the tailwater would probably be optimized for the aquatic community as a whole if the water quality and habitat requirements of the target species are met. Alternatively, the target species could be a critical part of the community because of its role in nutrient cycling or energy flows. Thus, prey fish (such as many species of minnows) or benthic organisms can be selected as target species or as target groups.

2.9.2.2 In some cases, an endangered or threatened species could potentially be selected as the target species. However, the flow and water quality requirements of threatened and endangered species are usually narrow or poorly known. Consequently, it is doubtful that a reservoir project could consistently release flows of the necessary quality and quantity to meet the requirements of these organisms.

2.9.2.3 Once a target species is selected, a decision must be made as to how best to quantify the water quality and quantity requirements of the target species. Two approaches that have been successfully used are available. The first is based on the assumption that no particular portion of the life-history cycle is critical or limiting to the abundance of the species in the tailwater. The problem then distills to a matter of selecting a reach representative of the entire tailwater. The conditions necessary to meet the requirements of the species in the "representative reach" are derived from the literature or estimated in studies. The project is operated to discharge water of the required quality and quantity to meet the requirements of the target species in the representative reach. These releases would be beneficial for the target species throughout the entire tailwater since the representative reach is reflective of conditions in the entire tailwater.

2.9.2.4 Alternatively, an evaluation of the target species may indicate that it is limited only during a portion of its life cycle. For example, the abundance of a tailwater fish species may be limited by availability of spawning habitat during the reproductive period, and the conditions in the tailwater during other periods of the year are generally not important in determining the abundance of the organism. In this case, the project is operated to optimize conditions for spawning in the "critical reach" of river in which spawning occurs during the spawning season. Conditions during other periods of the year or other river reaches are not considered to be limiting to the target species.

2.9.2.5 Further information on target species selection can be obtained from US Fish and Wildlife Service (1980) and Bovee (1982).

2.9.3 Recommendations

2.9.3.1 Ideally, a tailwater target species should be selected during the planning stage of a reservoir project in conjunction with State and Federal fishery agencies. Habitat, water quality (particularly temperature and DO) and flow requirements of the selected target species should be identified and compared to both capabilities of the project and constraints imposed by authorized project purposes. Detailed water quality modeling (see section 2.3, "Useful Simulation Techniques for Reservoir Release Applications") of the reservoir and tailwater can be used for this purpose. The Physical Habitat Simulation System (see sections on minimum low flows in regard to both hydropower (paragraph 3.2.2) and flood control (paragraph 4.4)) can be used to predict physical habitat quality at different flows. Target species requirements can then be compared to project capabilities. If the target species requirements cannot be reconciled with the capabilities of the project, then either project design and operation must be modified or a different target species must be selected. For example, a put-and-take trout fishery downstream from a small flood control project on a formerly warmwater stream could be jeopardized by poor water quality often associated with deep release; furthermore, the storage of cold water in the hypolimnion may be inadequate to guarantee flows of suitable temperature in late summer or early fall. Smallmouth bass would be a better tailwater target species for this situation, assuming that physical habitat was suitable. Use of the critical reach (see paragraph 2.9.2.4) approach should generally be avoided near the project (within

3 kilometers). The critical reach approach usually indicates that a section of river is being used for spawning or rearing. The flow and water quality requirements for spawning and rearing are usually very narrow, and the project may be unable to consistently meet these requirements while simultaneously meeting other project purposes.

2.9.3.2 Effects of a reservoir on endangered or threatened species that occur downstream must be considered according to the Endangered Species Act. The habitat requirements of threatened and endangered species are often very narrow or poorly known. In some instances, studies may be necessary to define the life requirements of these species. Section 7 of the Endangered Species Act may require that the project be specifically operated to prevent habitat degradation of the subject species.

2.9.4 References

Bovee, K. D. 1982. "A Guide to Stream Habitat Analysis Using the Instream Flow Incremental Methodology: Instream Flow Information Paper No. 12." FWS/OBS-82/26, US Department of the Interior, Fish and Wildlife Service, Fort Collins, Colo.

US Fish and Wildlife Service. 1980. Habitat Evaluation Procedures, US Department of the Interior, Fish and Wildlife Service.

PART 3. PEAKING HYDROPOWER TOPICS

3.1 Background

3.1.1 The general environmental impacts associated with hydropower generation are in part determined by the type of power demand that a reservoir project is designed and operated to meet. A full understanding of the environmental impacts of hydropower production requires a basic knowledge of the temporal pattern of power demand.

3.1.2 Demand for power can be broadly classified as base load or peaking power (Figure 4). Base load, represented by the area below the horizontal reference line in Figure 4, is the quantity of power required at all times. Run-of-the-river projects are operated to meet demand for base load. These projects typically are small (compared to a peaking project on the same system), have a short hydraulic residence time, and release discharges that usually approximate inflows. Run-of-the-river projects (that are not part of a reservoir system) characteristically release constant (nonfluctuating) discharges over relatively long time periods.

3.1.3 Peaking power is the quantity of power needed to satisfy daily peak demands for power. Reservoir projects are ideal sources of peaking power because hydroturbines can come on-line much more quickly than coal-fired or nuclear power plants. In fact, the response time (the length of time between notification of need for power and the generation of power) of hydropower projects usually does not exceed several minutes. Ordinarily, peak demand occurs from midmorning through the late evening on weekdays (Figure 4), although exceptions to this pattern are common. Peaking power projects typically are larger than run-of-the-river projects on the same system, have a long hydraulic residence time, and, because of their greater capacity, can store flows during high runoff periods for use in generating power during periods of low inflow. Thus, these projects can guarantee a substantial amount of firm power throughout the year. Although peaking and run-of-the-river operation are most common at CE projects, intermediate types of power generation

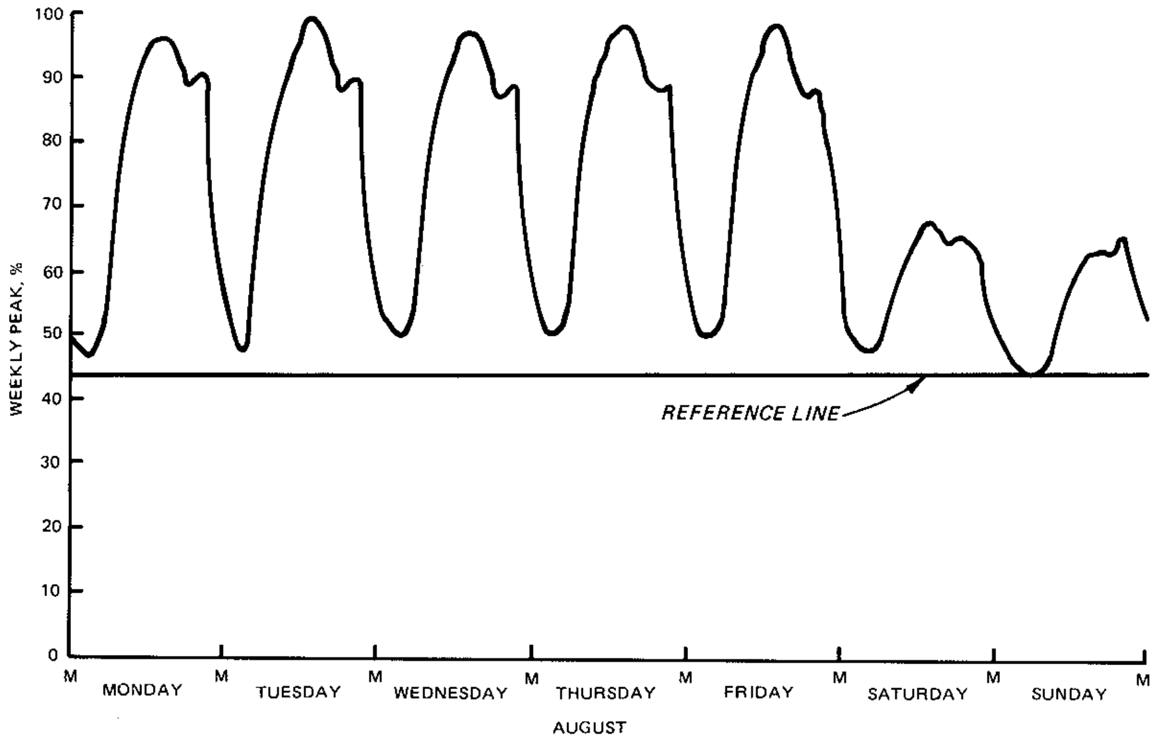

Figure 4. Typical variations in weekly power demand. Peak demand is represented by the area above the horizontal reference line and base load falls below the horizontal reference line. Note that demand diminishes substantially during the weekend

can also occur. This part of the report will document only the downstream effects of peaking hydropower generation.

3.1.4 Identification of the downstream environmental effects of peaking hydropower operation is usually confounded by two factors. First, the downstream effects of peaking hydropower operation are partly determined by the impacts associated with reservoir projects in general. These effects include seasonal alterations in water quality, alteration in downstream sediment transport, and seasonal modifications in the yearly hydrograph. Second, the downstream effects of peaking hydropower operation are often confounded with the effects of deep release since most peaking projects have only deep-release capability. Many studies of the effects of peaking projects have incorrectly related effects of deep release to those caused by peaking operation. These misconceptions must be reconciled with actual environmental effects if the impacts of peaking hydropower generation are to be successfully ameliorated.

3.1.5 Operation of a reservoir project for peaking hydropower production alters the preimpoundment riverine environment by changing both seasonal and daily flow patterns. Seasonal flow patterns are altered because seasonal high flows are at least partly retained for generation during low-inflow periods and also because reservoir projects authorized to generate peaking power usually have flood control as an authorized project purpose. (Refer to section 4.1 for an explanation of the downstream effects of flood control operation.) Daily flow patterns are altered because releases are determined by daily demands for electrical power and not by short-term precipitation patterns within the basin. The extent of daily flow alteration is determined by the timing of demands for peaking power and the generation capacity (discharge) of the project relative to the channel capacity. Substantial daily fluctuations in water level can occur downstream as the project abruptly releases large amounts of water during generation following periods of reduced discharge. Increased discharges into the tailwater result in substantial increases in water depth and velocity over nongeneration periods.

3.1.6 Minimum low flows are released from a peaking hydropower project following generation periods. Minimum low flows can vary from near zero (only seepage) to a significant percentage of the mean daily flow. The ranges in flow downstream from a peaking hydropower project are usually much less than the preimpoundment yearly extremes. However, the environmental effects of peaking operation can be substantial because downstream flow fluctuations occur daily and not seasonally. Thus, preimpoundment minimum low flows occur relatively infrequently and tend to fall within certain seasons as part of a predictable, natural cycle, but minimum low flows from peaking projects occur year-round on a daily basis.

3.1.7 Peaking hydropower operation can result in more substantial downstream changes in physical habitat than nonhydropower operation.

Not only is the downstream transport of sediment interrupted by the reservoir, but the highly fluctuating flows may also increase bed scour, armoring, and bank sloughing and decrease stream gradient (caused by channel degradation near the project and increased sediment redeposition farther downstream). The extent of physical habitat modification (channel change) is determined by channel bed and riverbank composition and the velocity of the releases in the tailwater. Changes in physical habitat in the tailwater are most pronounced during the first several years of project operation. Over a period of years, the channel reaches a near-equilibrium state and further channel changes become minor.

3.1.8 Peaking hydropower operation can alter downstream water quality. Water quality of hydropower releases is determined by chemical and physical conditions in the reservoir at the depth of withdrawal and by changes occurring during passage of the water through the conduits, turbines, and stilling basin. A sufficient understanding of in-pool reservoir water quality necessary to understand reservoir impacts on the tailwater can be obtained by reading the general discussion on effects of impoundments on downstream water quality (see section 2.2). The user is also advised to consult section 2.4 of this handbook for a discussion of the effects of deep release, since effects of peaking hydropower operation are often confounded with effects of deep release.

3.1.9 Significant short-term changes in water quality can occur in the tailwater if reservoir water quality at the depth of withdrawal is dissimilar from equilibrium conditions in the tailwater. These changes often occur after long periods of minimum release, during which time water quality of the tailwater has been altered by insolation, photosynthesis, and other biogeochemical processes. The release of water from the reservoir into the tailwater will then cause extremely rapid changes in water quality as the water in the tailwater is replaced by reservoir discharges.

3.1.10 The downstream extent of the reservoir's influence depends upon the difference between water quality at the depth of withdrawal and the equilibrium water quality of the river, the discharge rate, meteorological factors, and physical, chemical, and biological processes in the river such as oxidation, reaeration, respiration, and photosythesis. Local conditions will eventually characterize individual tailwaters.

3.1.11 This section of the report contains topics discussing the downstream environmental quality effects associated with peaking hydropower production. However, several of these topics ("Impacts of Daily and Weekly Minimum Flows," "Impacts of Peaking Flows," and "Impacts of Highly Fluctuating Flows") are closely interrelated by reservoir hydrology even though their environmental effects can be described separately. For example, an increase in the minimum low-flow release results in a decrease in water-level fluctuations and either a decrease in generating flows or a shortening of the time that the project releases generating flows since, for any given time, there is a constant volume of water in the reservoir available for discharge. Thus, to gain a complete understanding of these effects of peaking hydropower generation on downstream environmental quality, one should consult all three of these topic areas.

3.2 Impacts of Daily and Weekly Minimum Low Flows

3.2.1 Topic Description

Releases from peaking hydropower projects reflect demands for electricity. Minimum daily low flows are released when demand for peaking power diminishes, usually early in the morning and at night. Minimum weekly low flows occur on Saturday and Sunday since demand for power is least on weekends. Minimum low-flow releases from a peaking hydropower project may be inadequate to meet the instream flow needs of tailwater biota. Inadequate minimum flows downstream from peaking hydropower projects are documented to have serious effects on tailwater biota. Consequently, establishing a minimum low-flow release that maintains the tailwater aquatic community becomes a legitimate concern in the operation of a reservoir project.

3.2.2 Discussion

3.2.2.1 Tailwaters of peaking hydropower projects often alternate between dewatering during nongeneration and channel capacity flows during full generation. Inadequate minimum low-flow releases during nongeneration can stress tailwater aquatic organisms in a number of ways. The carrying capacity of the aquatic habitat remaining in the tailwater may be substantially reduced as the wetted perimeter of the channel decreases with decreasing discharge. Riffle areas (which produce much of the fish food in the river) may dry out, leaving only a series of pools as refugia for aquatic organisms. Sessile organisms in riffle areas and shallows of the tailwater are desiccated and mobile organisms are concentrated into remaining pool areas, resulting in increased competition for food and space. Predation within the pool increases both by aquatic organisms and by terrestrial and avian predators (raccoons, kingfishers, herons). Reduced water velocities also decrease the drifting fish food and the food (fine particulate organic matter) to filter-feeding invertebrates. The nesting sites of fish may be dewatered with attendant mortality of eggs and fry. Also, in these pools, effects of poor water quality may be intensified, particularly in the case of summer low flows where DO depletion, increased water temperature, and reduced water velocity may occur. In coldwater tailwaters, effects of excessively warm water may be detrimental or lethal to coldwater fishes (trout) and many invertebrates. Inadequate weekend minimum low flows have the potential to be deleterious, particularly over hot summer weekends when cold water released from a project can warm to near lethal levels over a 2-day period. Release of cold water on a Monday may also result in thermal shock to aquatic organisms in the tailwater. Inadequate winter low flows may subject aquatic biota to freezing, complete ice cover, anchor ice formation, and other harsh climatic conditions.

3.2.2.2 Maintenance of suitable habitat for tailwater biota during nongeneration will alleviate many of the detrimental impacts associated with inadequate minimum low flows. However, many older peaking hydropower projects do not have the capability to release low flows that meet instream flow needs. Low flows cannot be released through the turbines since turbines cannot be operated substantially below their rated capacity without extensive maintenance. Floodgates composing part of the outlet works of a peaking hydropower project are generally unable to discharge low flows because the gates cannot be operated with the necessary precision or because they vibrate violently when attempting to pass low flows under high hydrostatic head.

3.2.2.3 Two structural alternatives are available to provide adequate downstream flows during nongeneration periods. One is to construct and operate a reregulation dam downstream from the peaking hydropower project. The reregulation dam stores a portion of the generating flows and releases them slowly until peaking operation begins again. Another structural alternative is to excavate deep pools in the tailwater to provide sufficient refuges for fish and invertebrates during nongeneration periods. In coldwater fisheries located on formerly warmwater streams, pools should be sufficiently deep to provide adequate storage of cold water to last through a summer weekend without warming to a lethal temperature. If possible, channels should connect pools to allow movement of fish between the pools during nongeneration periods. Physical characteristics of tailwater modifications needed to supply habitat during generation can be roughly determined by performing an analysis using the Physical Habitat Simulation (PHABSIM) system developed by the Western Energy and Land Use Team of the US Fish and Wildlife Service (Milhous, Wegner, and Waddle 1984). Use of PHABSIM for this purpose may be quite difficult, and the user should contact WES for assistance.

3.2.2.4 An operational alternative is to release a minimum low flow during nongeneration periods if the structure is designed with the appropriate type of outlet works. Several alternatives are available if the structure does not have the capability to release a controllable low flow. Low-flow bypass gates that can regulate releases to less than 1 cu m/sec should be considered. Sluice gates can be designed to incorporate low-flow piggyback gates to release minimum low flows. A small service generator can provide power for the project and also supply flows to the tailwater during nongeneration.

3.2.2.5 For any of these operational alternatives, water quality (particularly temperature) of the low-flow releases should approximate water quality of the generation releases. The outlet structure that releases the minimum flow to meet downstream instream flow needs should be controllable to release a range of minimum flows since minimum flow criteria may change seasonally. Special weekend releases should be considered to maintain suitable downstream water temperatures, particularly on coldwater fisheries located on formerly warmwater streams.

3.2.2.6 There are two general approaches for determining the minimum reservoir releases necessary to sustain tailwater biota. The first relies on historical flow records from the preimpoundment stream or is based on the size of the drainage basin. Flows similar to the historical low flows are used as minimum flow rates. The rationale is that historic low flows have not permanently disrupted the biota; therefore, they would not harm the biota in the tailwater. However, the effects of historical low flows such as the 7Q10 (lowest 7 consecutive-day flow over a 10-year period) on an unregulated stream is probably much less than the effects of the 7Q10 released over long time periods (months) during each portion of the year. In the former case, the minimum flow has a reoccurrence probability for any given year of 0.10; in the latter case it may reoccur many times in the course of 1 year. Although the 7Q10 flow is generally considered inadequate for downstream environmental quality protection, other low-flow recommendations based on historical flow records (i.e. Tennant or Montana Method) or water yield (Connecticut Method) have been used or proposed on a regional basis. These types of methods require neither a target species nor the collection of field data. Their general drawbacks are that they are not generally accepted nor have they ever been tested or verified. Also, because of their general nature, they cannot be structured to protect a particular community, species, or life stage.

3.2.2.7 The second type of approach estimates available habitat for a selected species at different discharges. The lowest discharge that maintains suitable habitat for the target species is recommended as the minimum low flow. In some cases, the flow recommendation can be used to protect a particularly sensitive portion of the species life history (such as spawning or larval development). This type of approach generally involves hydraulic description or simulation to predict the distribution of depths and velocities in a reach at different discharges. These values are then evaluated against the known preferences (suitability curves or preferenda) of the target species to assess the habitat value at each discharge. The results are generally presented as the habitat measure "weighted usable area" (in increments of area of river per linear stream distance) versus discharge (see Figure 5).

3.2.2.8 An intermediate approach is to examine the change in wetted perimeter at different discharges since wetted perimeter is often a measure of the carrying capacity of the system for benthic (fishfood) organisms. Thus, a substantial decrease in the wetted perimeter of the stream will result in a reduction in the capacity of the tailwater to produce fish food.

3.2.2.9 The volume of releases needed to maintain the downstream

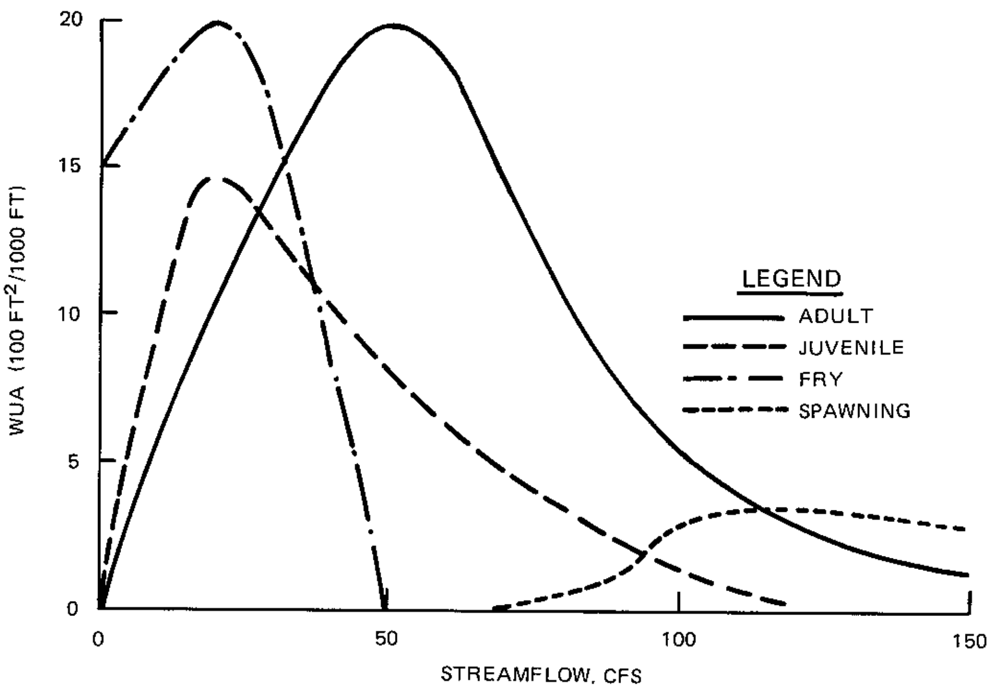

Figure 5. Example plot of weighted usable area (WUA) versus stream flow. The WUA is a measure of the quality of the stream for the target species or group. Increased WUA indicates an increase in the value of the stream habitat for the target species. (Factors for conversion of non-SI units of measurement to SI (metric) units are given on page 4)

ecosystem or a particular target species can be determined by performing an instream flow study using PHABSIM. However, performing a defensible instream flow study is a complex and difficult undertaking, and the user is referred to Milhous, Wegner, and Waddle (1984) and Bovee (1982) for further guidance on this topic. Currently, documentation for the PHABSIM system includes instructions for simulating habitat at different discharges under steady-flow conditions only, thus limiting its application downstream of peaking hydropower projects. Personnel from WES can assist with applying PHABSIM downstream from a peaking hydropower project.

3.2.2.10 Several factors must be considered during the performance of an instream flow study at CE reservoir projects. First, one must be aware that a poorly performed instream flow study that overestimates flow needs for tailwater biota can result in a substantial loss of revenue over the life of a peaking hydropower project. Conversely, a valuable downstream natural resource can be jeopardized if the instream flow needs of tailwater biota are underestimated. Therefore, to ensure the formulation of defensible release guidelines, personnel from the CE District office should be directly involved in the performance of an instream flow study to determine the flow requirements of tailwater biota at CE projects.

3.2.2.11 Second, the reservoir surface elevation is partly determined by the discharge patterns of the project. If discharges exceed inflows, then the reservoir surface elevation (and surface area and volume) decrease. Conversely, if inflows exceed discharges and withdrawals, then the reservoir elevation (and surface area and volume) must increase. Since the reservoir fishery dynamics are largely determined by seasonal water-level fluctuations, efforts to enhance downstream habitat by increasing discharges during drought conditions may have a detrimental effect on the reservoir fishery. Therefore, effects of efforts to optimize conditions for fish populations downstream of the reservoir must be balanced against the effects these efforts have on the reservoir fishery. If possible, the reservoir and downstream reaches should be managed as an integrated unit. Methods to assess the effects of seasonally fluctuating water levels on reservoir fish can be found in Ploskey (1982, 1983) and Ploskey, Nestler, and Aggus (1984).

3.2.2.12 Third, most CE projects are fundamentally different than the projects originally associated with the instream flow issue. The projects with which the instream flow issue originally arose are primarily used to provide for irrigation and water supply (long-term out-of-stream uses), whereas in most CE projects, the water remains in the system. Thus, the issue for peaking hydropower projects is not how much water should be allocated on a seasonal basis for fisheries maintenance but rather what is the minimum flow necessary to maintain the fishery during nongeneration.

3.2.2.13 Fourth, most commonly used methods to determine flow regimes to maintain downstream organisms are based on the notion of a "target species," that is, a species of aquatic organism that is valuable in its own right or representative of the requirements for the entire community. Selection of appropriate target species is one of the most important considerations when determining downstream flow needs of the aquatic community. Further information on this topic is provided in section 2.9 of this handbook.

3.2.2.14 In addition to flow modification, physical changes (habitat improvement) can be used to increase the habitat available downstream from reservoir projects during seasonal minimum low flows. Further details on methods to improve instream habitat can be found in Shields and Palermo (1982). For example, wing dikes could concentrate flows to the center of the channel to provide a target species or group with increased water velocity during minimum low-flow periods. Areas behind the wing dike can provide shelter for tailwater fish during high flows.

3.2.3 Recommendations

3.2.3.1 Two structural methods are available to provide habitat for tailwater biota during nongeneration periods. Reregulation dams can provide steady flows intermediate between generation and nongenration discharges. However, the in-pool environmental consequences of reregulation dams are not well documented. An evaluation of the quality of the physical habitat within the reregulation pool is not possible with the present state of the art. The in-pool habitat created by the reregulation dam may be of marginal value and, therefore, the river reaches flooded by the reregulation dam may be lost to the system in efforts to improve conditions further downstream. If a reregulation dam is considered as an alternative to provide minimum flows to meet downstream instream flow needs, then at a minimum, the field office should consider a detailed water quality study to describe conditions within and downstream of the impoundment created by the reregulation dam. A reregulation dam can have a considerable effect on downstream water quality by altering reaeration rates, increasing water temperatures, and changing concentrations of other water quality constituents. A water quality study can provide guidance on the best design for the outlet works of the reregulation dam to minimize some of these effects.

3.2.3.2 Habitat for tailwater biota during nongeneration can also be provided by excavating pools in the tailwater. Although firm evidence is not yet available, excavation is probably the least desirable alternative since the tailwater will then consist of a series of lentic (lakelike) habitats during nongeneration and a lotic (riverine) habitat during generation and will alternate between these two very different habitats on a daily basis.

3.2.3.3 Based on the present state of the art, release of a minimum low flow that maintains tailwater biota is the most defensible alternative for providing habitat during nongeneration. The PHABSIM system is the most widely used and accepted method to determine the flow requirements of tailwater organisms. PHABSIM should be used downstream of CE peaking hydropower projects to establish minimum low flows that protect valuable downstream fishery resources from effects of inadequate flows during nongeneration.

3.2.3.4 Detailed guidance on the performance of an instream flow study is beyond the scope of this handbook; the user should consult Bovee (1982) and Milhous, Wegner, and Waddle (1984) for further information on this topic. General guidance can be provided to ensure that the most defensible study is performed. An instream flow study is a complex undertaking that involves a knowledge of aquatic ecology, fishery biology, hydraulic simulation, water quality modeling, and potamology. Ordinarily, a single individual or even a single agency lacks the technical expertise to adequately perform a defensible study, particularly for a complex river system. Thus, an instream flow study should be viewed as a multidisciplinary, cooperative effort between agencies whose mission includes responsibility for the stream in question. This approach also ensures that most of the institutional misunderstandings between agencies that may arise concerning an instream flow study can be resolved during the course of the study rather than at the conclusion of the study, during the review process. To this end, the study team for an instream flow study sponsored by the CE should include one knowledgeable representative of the CE District office.

3.2.4 References

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Shields, F. D., Jr. and Palermo, M. R. 1982. "Assessment of Environmental Considerations in the Design and Construction of Waterway Projects," Technical Report E-82-8, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

3.3 Impacts of Peaking Flows

3.3.1 Topic Description

High discharges are released from peaking hydropower projects during generation periods when demand for power increases, usually from mid-morning until late in the evening, although this schedule can vary considerably. During generation, tailwater biota experience high water levels, high current velocities, and a rapid change in water quality from nongeneration periods. High discharges may have a detrimental effect on tailwater biota.

3.3.2 Discussion

3.3.2.1 In unregulated streams, flows are determined primarily by precipitation patterns in the watershed. Flows range from very low (approaching zero in some cases) to flood flows that exceed channel capacity, with most flows at an intermediate level. In addition, the rate of change from one flow to another is usually very gradual in unregulated systems. Discharges from peaking hydropower projects differ considerably from unregulated systems because flows are concentrated near the minimum discharge and generation discharge. The generation flows are less than the preimpoundment flood flows, although the generation flows occur much more frequently than natural high flows, often on a daily basis (Figure 6).

3.3.2.2 Generation flows have been thought to disrupt the natural behavior of some aquatic organisms and result in a general degradation of habitat available for tailwater organisms. However, these effects should, in many cases, be more correctly associated with either the effects of deep release, the extent of flow fluctuation (the difference between the minimum and maximum flow) in the tailwater, inadequate minimum low flow, or the initial surge associated with generation. For example, density of entrained (swept up by currents) invertebrates is much greater during the surge period, when tailwater flow conditions change from low flow to generation flows, than during generation flows. Concomitantly, changes in physical habitat in the channel resulting from

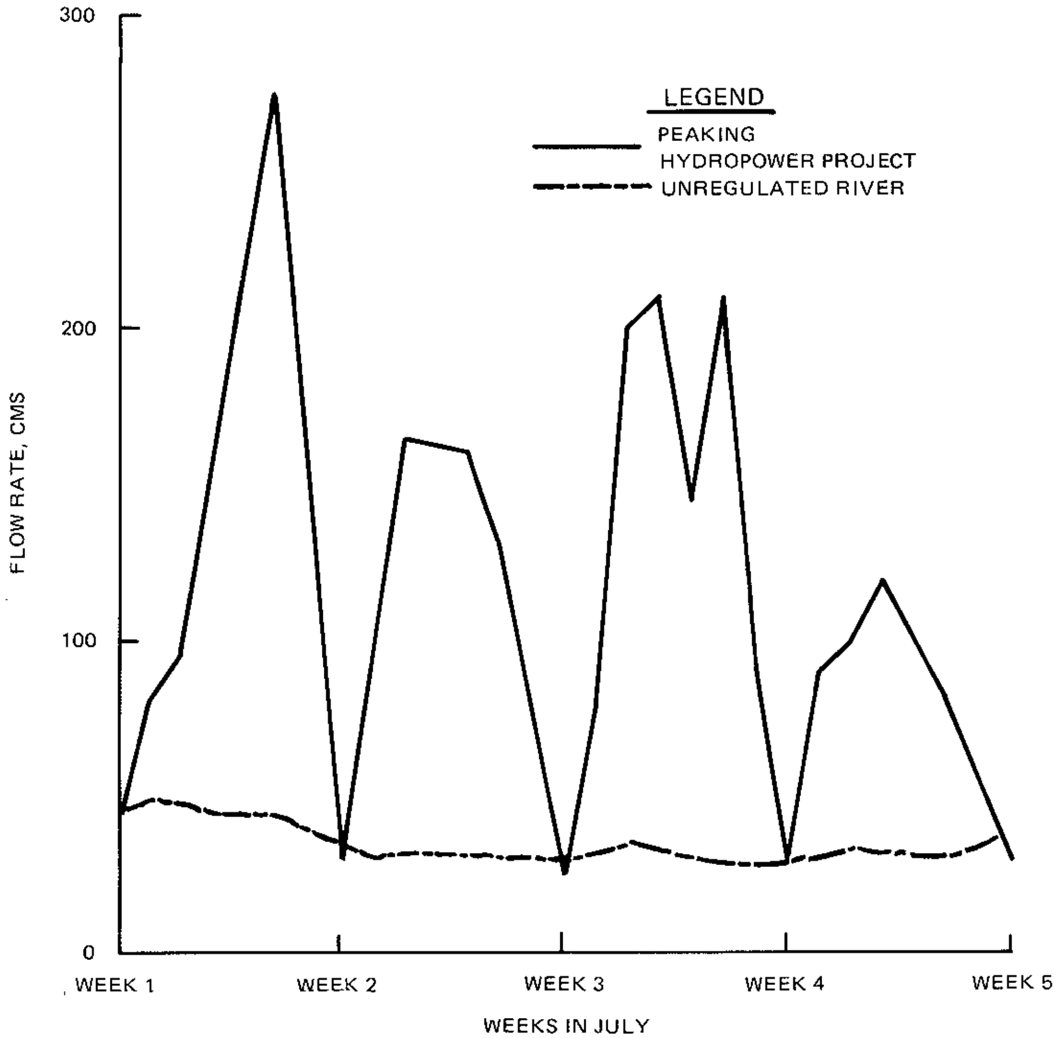

Figure 6. Comparison of mean daily flows from a peaking hydropower project with flows in an unregulated river of the same approximate channel width. Note the reduced weekend releases and increased weekday releases that reflect demand for power.

scour and armoring are caused not only by the generation flows, but also by the extent and rate of water-level fluctuation and the sediment-trap effect of the impoundment. Generation flows can result in some scour of benthic organisms and dislocation of fish. However, generating flows usually do not cause significant catastrophic downstream movement of either fish or invertebrates, especially if physical cover such as boulders, backwaters, and deep pools outside the flow channel are available as refuges for tailwater fish. Few detrimental effects that can be assigned exclusively to the effects of generation flows are documented.

3.3.2.3 Generation flows can extend the downstream effects of poor release water quality. Generation flows carry water of poor quality farther downstream since the increased discharges result in both increased current velocity and a decrease in the surface:volume ratio of the flows, thereby reducing the rate at which the water quality of the releases reaches equilibrium with atmospheric and meteorological influences. Water quality models that can predict the downstream extent of poor water quality are available and should be considered if the downstream extent of poor water quality is a concern (see section 2.3 for more information).

3.3.3 Recommendations

Downstream environmental consequences of high flows associated with peaking hydropower generation are generally less severe than other consequences of peaking power generation, such as lack of an adequate minimum low flow or extreme daily fluctuations in discharge. Also, the nature of generation releases provides little opportunity for ameliorative action. If the tailwater is devoid of physical cover for fish, that is, if deep pools do not exist or boulders or backwaters are not present, some thought should be given to providing structures as refuge from high currents.

3.4 Impacts of the Initial Surge of Water Associated with Start-Up

3.4.1 Topic Description

An initial surge of water is released into the tailwater during start-up of the turbines at a peaking hydropower project. Downstream environmental effects of the initial release surge are separate and distinct from the effects of sustained generating flows. The surge period is characterized by highly turbulent flows and rapid changes in depth, velocity, water temperature, and water quality. Although the initial surge associated with start-up usually lasts less than 30 min, it does have the potential to severely impact water quality and aquatic biota in a tailwater.

3.4.2 Discussion

3.4.2.1 The initial discharge surge during start-up of the turbines at a peaking hydropower project follows a period of minimum low flow that may have lasted from several hours (from one weekday to another) to several days (from Friday to Monday). The discharge surge during start-up of generation has a substantial effect on physical and chemical conditions in the tailwater. The physical effects are related primarily to the large flow gradients of the initial release. The large flow gradients may accelerate erosion, scour, and armoring in the channel. In addition, the surge may scour macrophytes, periphyton, and macroinvertebrates from the streambed (see Figure 7, periphyton are estimated as chlorophyll-a and macrophyte biomass are presented as particulate organic matter). Additionally, the surge may disorient and entrain tailwater fish.

3.4.2.2 Effects of start-up of generation on water quality are related to ambient meteorological conditions relative to the length of the nongeneration period preceding start-up and water quality at the depth of release. Local meteorological conditions can substantially alter water quality of the releases during long periods of nongeneration if the water quality at the depth of withdrawal is considerably different from equilibrium water quality. Water quality in the tailwater can

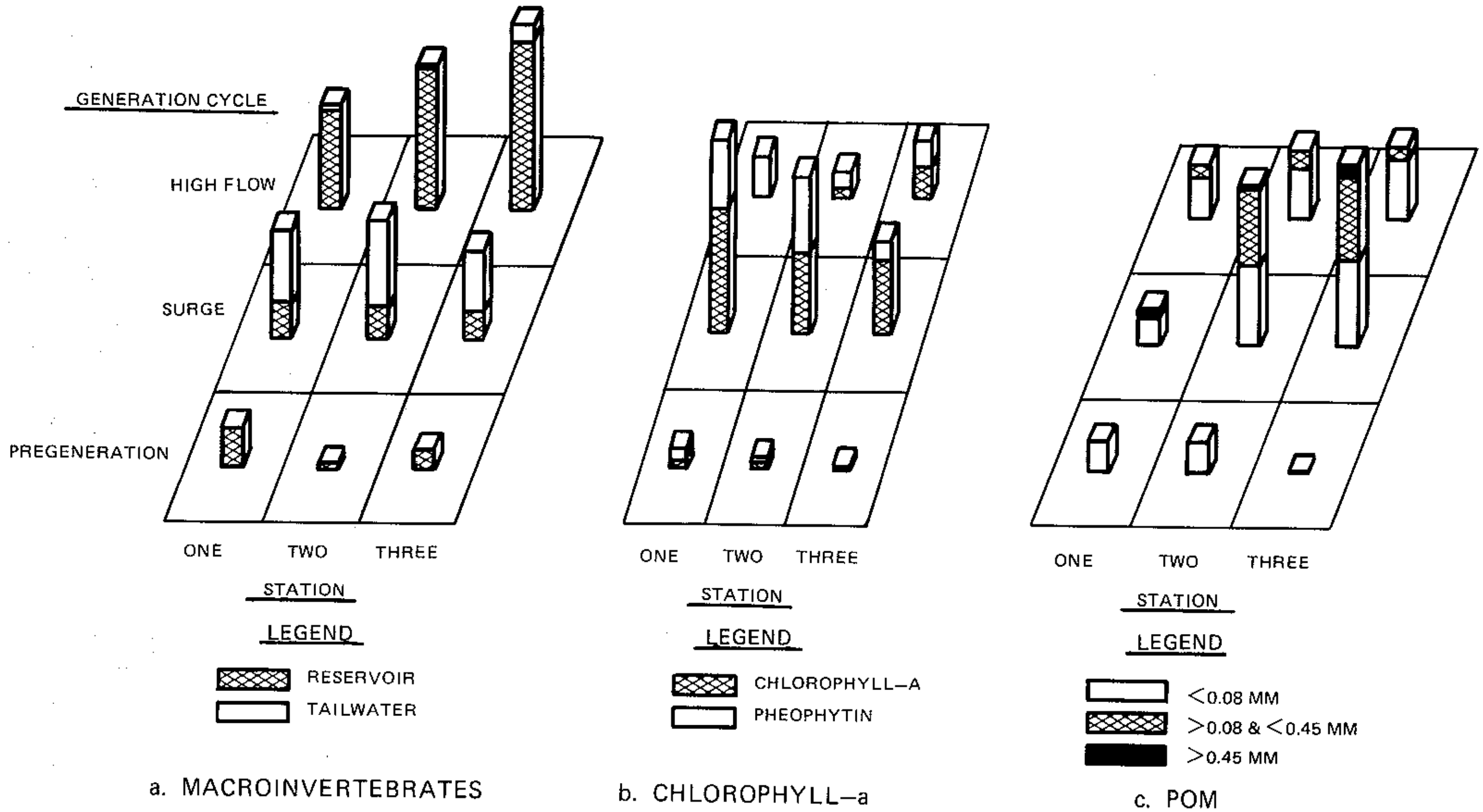

Figure 7. Estimated densities of macroinvertebrates, chlorophyll-a, and particulate organic matter during a generation cycle at a peaking hydropower project

change suddenly as generation releases flow through the tailwater (Figure 8). Extreme changes in water quality during start-up may result in thermal and chemical shock to aquatic organisms.

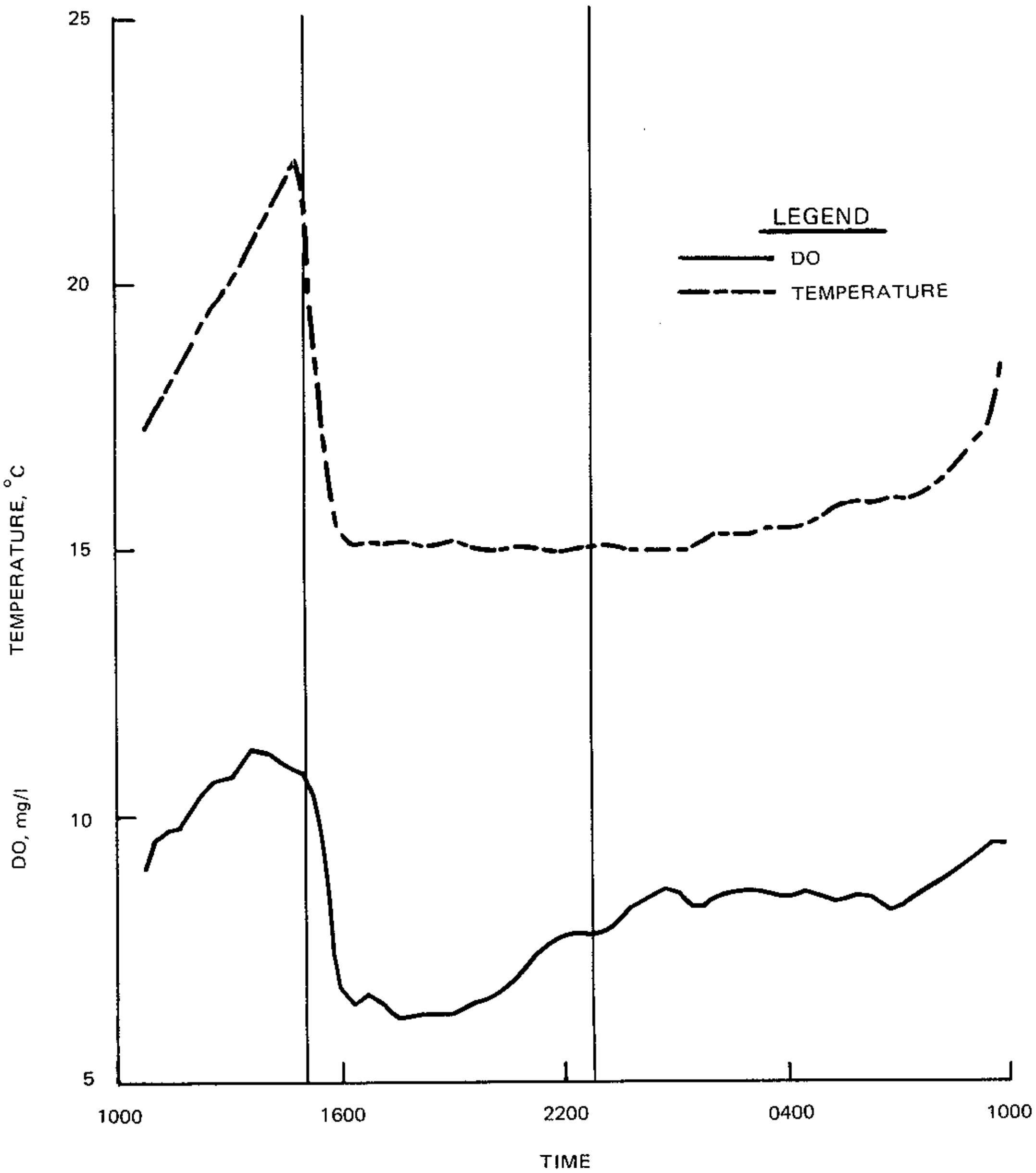

Figure 8. Changes in temperature and dissolved oxygen (DO) 4.5 km downstream of Lake Hartwell Dam during a July generation cycle. The vertical reference lines represent the passage of the intitial surge (1500 hr) and the end of generation (2245 hr). Note the decrease in temperature and DO at the surge and the general increase in these parameters during nongeneration

3.4.3 Recommendations

Downstream environmental impacts of the initial surge associated with start-up at a peaking hydropower project can be ameliorated in several ways. First, the start-up of the turbines can be staged. For example, if six turbines of equal capacity are located at a project, the first turbine should come on-line at the time of power demand. The second turbine should come on-line at least 20 min after the first (thereby doubling the generation flow). The remaining turbines should be brought on-line at least 20 min after the second turbine has been brought on-line. Alternatively, the rate of rise of tailwater water levels can be regulated. For example, the rise in water levels can be limited to 1 foot per hour or less. Extreme short-term changes in water quality during the surge period can be avoided by blending hydropower releases with spillage.

3.5 Impacts of Highly Fluctuating Flows

3.5.1 Topic Description

Discharges from a peaking hydropower project cycle between generation flows (up to and perhaps exceeding channel capacity) and nongeneration flows (as low as seepage). The difference between generation discharge and nongeneration discharge represents the extent of water-level fluctuation. Although the amplitude of hydropower water-level fluctuations may be equivalent to the amplitude of flows in the unregulated river, the frequency of major fluctuations, the rate of change of water levels, and the duration of a given water level in the tailwater are drastically altered. Highly fluctuating flows may have a negative effect on tailwater biota.

3.5.2 Discussion

3.5.2.1 Highly fluctuating water levels can affect tailwater biota directly through frequent alterations in depth and velocity over short time periods. The sudden changes in flow conditions may exceed the rate at which aquatic biota can adjust to new habitat conditions, resulting in either stranding at low flows or entrainment at high flows. In fact, highly fluctuating discharges that vary rapidly between seepage flows and channel-full flow exacerbate many of the deleterious effects of both minimum low flows (see section 3.2), generation surge (see section 3.4), and maximum generating flows (see section 3.3). Refer to the above-listed sections for more detailed information on the effects of highly fluctuating water levels.

3.5.2.2 The highly fluctuating water levels in the tailwaters of some peaking hydropower projects have biological impacts beyond those associated with minimum, maximum, and surge flows. Peaking hydropower projects can develop fluctuation zones in the tailwater that are unsuitable habitat for either terrestrial or aquatic organisms (only species of oligochaetes and chironomids are able to survive in the fluctuation zone). In many respects, the fluctuation zone may resemble the intertidal zone of some coastal areas. Many taxons of benthic insects, especially those considered quality fishfood such as mayflies, stoneflies, and caddisflies, cannot maintain populations in the fluctuation zone. The production of these fishfood organisms is then lost from the system.

3.5.2.3 Highly fluctuating water levels can also affect tailwater biota indirectly through long-term changes in channel geometry and substrate composition. These physical changes in the tailwater associated with fluctuating water levels may result in substantial habitat alterations. The information that follows provides a subjective description of the effects of highly fluctuating flows on physical habitat in tailwaters. Impacts of highly fluctuating water levels on physical habitat are associated with erosion (and consequent channel degradation), bank sloughing, sediment redistribution, and channel widening. The rate of erosion of streambeds and banks depends, among other things, on complex interrelationships of stream water velocity, suspended sediment concentration, channel gradient, composition of the streambed and banks, channel configuration, and channel alignment. The extent to which a given water-level fluctuation alters physical habitat in the tailwater is determined primarily by the composition of the substrate and channel bank. Substrates composed primarily of bedrock, boulder, cobble, or gravel tend to resist erosion by fluctuating water levels, whereas channels composed of fine, loosely compacted material tend to erode more easily. An exhaustive treatment of these interrelationships is beyond the scope of this document.

3.5.2.4 The potential for bank sloughing is related to the composition and water content of the channel banks. Water may saturate the channel banks either through ground-water inflow or as a result of stream water percolating into the bank when the water level is high (bank storage). Water-saturated channel banks will exhibit high pore-water pressures if the water level in the tailwater drops more rapidly than the bank storage can seep into the tailwater. The resultant high pore-water pressure can substantially reduce the stability of the banks, particularly if the banks are composed of alluvium, resulting in serious bank sloughing.

3.5.2.5 The severity of bank sloughing for a given tailwater is dependent upon the frequency and amplitude of water-level fluctuations. Pore-water pressure is directly related to the difference between the water table in the bank and the water level in the tailwater at low flow. Thus, large fluctuations in water level that often accompany peaking hydropower operations are especially conducive to bank sloughing as the streamflow varies from near-zero (dry channel) to channel capacity and back to zero in a matter of a few hours. Although unregulated streams may fluctuate in water level over similar ranges in response to stormflow, these natural fluctuations in water level are neither as frequent nor as rapid as may occur below dams operated to meet peak power demands.

3.5.2.6 The net effects of fluctuating water levels on the tailwater channel near the project are to increase erosion, increase bank sloughing, increase armoring, increase channel width, and decrease channel gradient. Farther downstream as peak discharges associated with generation decrease and the amplitude of water-level fluctuation attenuates, the net effect of fluctuating water levels is to increase sedimentation rates, as the sediment eroded near the project is redeposited downstream.

3.5.3 Recommendations

Tailwater water-level fluctuations are an unavoidable part of hydropower production, and little can be done to eliminate the effect of water-level fluctuations without directly impacting authorized project purposes. However, some deleterious effects of highly fluctuating water levels can be partially corrected. Recommendations for dampening the effects of highly fluctuating water levels are similar to recommendations for lessening the other impacts of peaking operation (nongeneration flows, generation flows, and start-up surge), since their deleterious effects are similar to those of highly fluctuating water levels. The direct effects (stranding, entrainment, exposure) of fluctuating water levels can be partially eliminated by releasing a minimum low flow sufficient to meet the flow requirements of downstream aquatic biota (see section 3.2 for more information on methods for determining minimum low flows), by staging the start-up of the turbines during the onset of generation (see section 3.4 for additional information on staging of turbines at start-up), and by limiting the rate of rise or fall of tailwater water levels. The indirect effects (changes in channel geometry and substrate composition) of highly fluctuating water levels on the tailwater ecosystem are too complex and interrelated to ameliorate by application of simple recommendations. If channel and bank substrate is predominantly unconsolidated material or alluvium, the advice of an expert in this area should be solicited.

3.6 Impacts of Hydropower Retrofit

3.6.1 Topic Description

Recent changes in legislation have made the development of hydropower at nonhydropower projects economically feasible. Water that was previously released from the project either through the sluice gates or over a spillway is instead diverted to a powerhouse for power generation.

3.6.2 Discussion

3.6.2.1 Case histories are not presently available to completely define the environmental impacts of hydropower retrofit at flood control projects. The following discussion is based on documented water quality and fishery dynamics both in the pool and downstream from flood control projects and how these dynamics may be impacted by hydropower development. This subject area requires further research to document actual downstream impacts and to develop complete guidance to avoid environmental quality degradation due to hydropower retrofit.

3.6.2.2 The downstream effects of hydropower retrofit that are separate from the effects of flood control operation are determined by the design of the outlet works and by the type of power demand (peaking or base-load) that the project provides. If the project will generate peaking power, the downstream effects will be largely similar to the effects described in earlier sections of this handbook (sections 3.2-3.5) under the topics "Impacts of Daily and Weekly Minimum Low Flows," "Impacts of Peaking Flows," "Impacts of the Initial Surge of Water Associated with Start-Up," and "Impacts of Highly Fluctuating Flows." Guidance on minimizing adverse downstream effects can be found in the recommendations section of each topic.

3.6.2.3 If flows are simply routed from the conduit to the powerhouse and no change in the daily or seasonal discharge pattern (hydrograph) or depth of withdrawal occurs, the downstream habitat and water quality effects may be negligible. However, if the project releases flows with seasonally low DO concentrations, the substantial reaeration that normally occurs as the releases pass through the outlet works of a flood control project may be lost. Normally, substantial reaeration does not occur in the conduits of hydropower projects.

3.6.2.4 The major downstream biological effect of hydropower retrofit of flood control projects will probably occur during hydropower operation during fall drawdown. Current evidence suggests that many of the fish in the tailwaters of flood control projects originate from within the reservoir. It appears that these fish pass through the floodgates and into the tailwater during fall drawdown, particularly if drawdown occurs after reservoir destratification. If the generating capacity of the retrofitted project is sufficiently large, much of the discharge to reduce the volume of the reservoir may pass through the turbines. The fish that ordinarily pass through the project may instead then pass through the turbines with the associated turbine mortality. Substantial fish movement may also occur during the winter during low pool conditions in the reservoir.

3.6.3 Recommendations

Hydropower retrofit of a flood control project will result in many of the environmental quality problems associated with peaking hydropower generation. Therefore, recommendations to alleviate these problems can be obtained by referring to the recommendations sections for topics 3.2-3.5. Detailed recommendations cannot be provided at this time for all aspects of hydropower retrofit because the environmental quality impacts are incompletely known. In general, the possibility of turbine mortality should be investigated for these projects. Additionally, the potential impact on downstream water quality of decreasing reaeration of the releases by diverting the releases from a sluiceway to a power conduit should also be investigated (Bohac et al. 1983, Wilhelms et al. 1986). A method is available to predict reaeration through a gated conduit (Wilhelms and Smith 1981). This reaeration would be lost with a hydropower retrofit.

3.6.4 References

Bohac, C. E., Boyd, J. W., Harshbarger, E. D., and Lewis, A. R. 1983. "Techniques for Reaeration of Hydropower Releases," Technical Report

E-83-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wilhelms, S. C., and Smith, D. R. 1981. "Reaeration Through Gated-Conduit Outlet Works," Technical Report E-81-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wilhelms, S. C., Schneider, M. L., and Howington, S. E. 1986. "Improvement of Hydropower Release Dissolved Oxygen with Turbine Venting," Technical Report in preparation, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

3.7 Impacts of Pumped-Storage Operation

3.7.1 Topic Description

Like peaking projects, pumped-storage projects are outfitted with turbines that generate electrical power to meet peak power demands. However, turbines at pumped-storage projects can be reversed and used as pumps to move water from a lower pool to an upper reservoir during periods of reduced demand for electricity so that the water can be again used to generate power at a later time. Pumped-storage operation is economically feasible because the price obtained for peaking power is substantially greater than the cost of baseload power. The increased price obtained for peaking power offsets the loss in efficiency associated with pumping back previously discharged flows during low-demand periods.

3.7.2 Discussion

3.7.2.1 Pumped-storage projects can be of various designs, requiring only the proximity of a downstream pool and an upstream reservoir. Water is discharged from the upper reservoir during generation and pumped back upstream during pumpback operation. The two reservoirs can be located on the same river system (in-line), or the storage reservoir can be excavated at some point away from the channel (off-line).

3.7.2.2 Certain environmental impacts of pumped-storage operation have been documented. However, many of the environmental quality impacts of pumped-storage operation are not sufficiently understood at this time to provide a complete discussion. Pumped-storage operation has the potential to alter water quality, particularly water temperature and stratification, in the primary storage reservoir. Although the detailed impacts of water quality alteration are site dependent, some general observations can be made. Pumped-storage operation generally lowers the thermocline, thereby increasing the heat content of the primary storage reservoir as well as increasing the temperature of the release water. Other water quality alterations are probable but have not been thoroughly documented.

3.7.2.3 Severe fish mortality has been documented during pumpback operation. Although fish mortality is generally not significant during generation, it can be severe during pumpback operation because of the relatively shallow depth of the intakes (draft tubes during generation) in the afterbay. During pumpback, water is withdrawn from near the surface of the downstream reservoir where the concentration of fish is usually higher than in the forebay. Consequently, fish are entrained during pumpback operation and may suffer turbine mortality. The level of turbine mortality of entrained fish is probably determined by turbine characteristics; wicket gate and blade settings; and the size, shape, abundance, and condition of fish in the afterbay. Mortality is not severe during generation because the intakes are usually located deep in the upper reservoir where the density of fish is generally low.

3.7.2.4 The potential for turbine mortality at pumped-storage projects is not the same throughout the year because fish congregate seasonally in tailwaters (in this case, in the afterbay of the pumped-storage project). Fish are normally most concentrated in the spring as upstream spawners are blocked by the dam, although other seasons may exhibit high concentrations depending on local conditions and fish species present in the downstream reservoir.

3.7.3 Recommendations

3.7.3.1 No generalized recommendations can be made at this time to avoid water quality problems associated with pumped-storage operation. If necessary, simulation methods (see paragraph 2.3.2.5) are available that can be applied to assess water quality alterations caused by pumped-storage operation.

3.7.3.2 Several recommendations can be made at this time to help avoid turbine mortality problems associated with pumped-storage operation; however, this topic area requires more research before completely defensible design and operation guidelines can be presented. The possibility of suspending pumpback when fish congregate in the tailwater (afterbay) should be considered, especially in the springtime since this time of year is when many warmwater fishes migrate upstream to spawn. In many cases, suspending pumpback operation in the spring may have little impact on project economics since heavy spring runoff may prohibit pumpback operation.

3.7.3.3 The use of fish diversion structures, such as traveling screens, block nets, bubble screens, and electrical screens cannot, at this time, be recommended since the performance of diversion structures has been neither consistent nor tested on projects the size of CE pumped-storage projects.

3.7.3.4 Particular care should be exercised during initial testing of pumpback capability because severe turbine mortality at this stage, even if it results from unique conditions that would not occur under routine operation, may jeopardize the operation of the project. Prior to testing, surveys of the fish community should be conducted to quantify the type and abundances of fishes in the afterbay. Testing should be delayed if fish are congregating near the powerhouse.

PART 4. FLOOD CONTROL OPERATION TOPICS

4.1 Background

4.1.1 Flood control refers to any effort designed to reduce a damaging stage or flow of water in a stream, floodway, lake, or coastal area. Flood control measures are often very complex in nature and may include the simultaneous operation of diversion structures, floodways, and reservoirs. This part of the handbook is restricted to a discussion of the downstream effects of flood control operation by a single-purpose or multipurpose reservoir. For more detailed information on the general topic of flood control, the reader should refer to several excellent texts on this topic, including Davis and Sorenson (1969) and Linsley and Franzini (1972).

4.1.2 The design and operation of a flood control project is a complex task based on detailed analyses of flow records, local and regional precipitation patterns, and local and regional topography. Often, a flood control project is operated as part of a basin or system plan to reduce flood damage. Because of these considerations, details of the design and operation of many flood control projects may be site specific. Nonetheless, certain patterns of operation are common to many flood control projects and can serve as a basis for understanding the downstream environmental effects of flood control operation.

4.1.3 The design and operation of flood control projects are primarily based on discharge patterns within the basin. In most regions of the country, precipitation (and consequently, runoff) is not evenly distributed through the year. Figure 9 presents a yearly hydrograph for a hypothetical unregulated stream. Note that high precipitation (and snowmelt) tend to concentrate in the winter and spring and are less common in the summer and fall. Thus, larger and more frequent floods tend to occur in winter and spring than in summer and fall, although flood flows may occur during any part of the year, particularly in smaller drainage basins. To minimize damage caused by flooding of an unregulated stream, a reservoir with sufficient storage capacity could

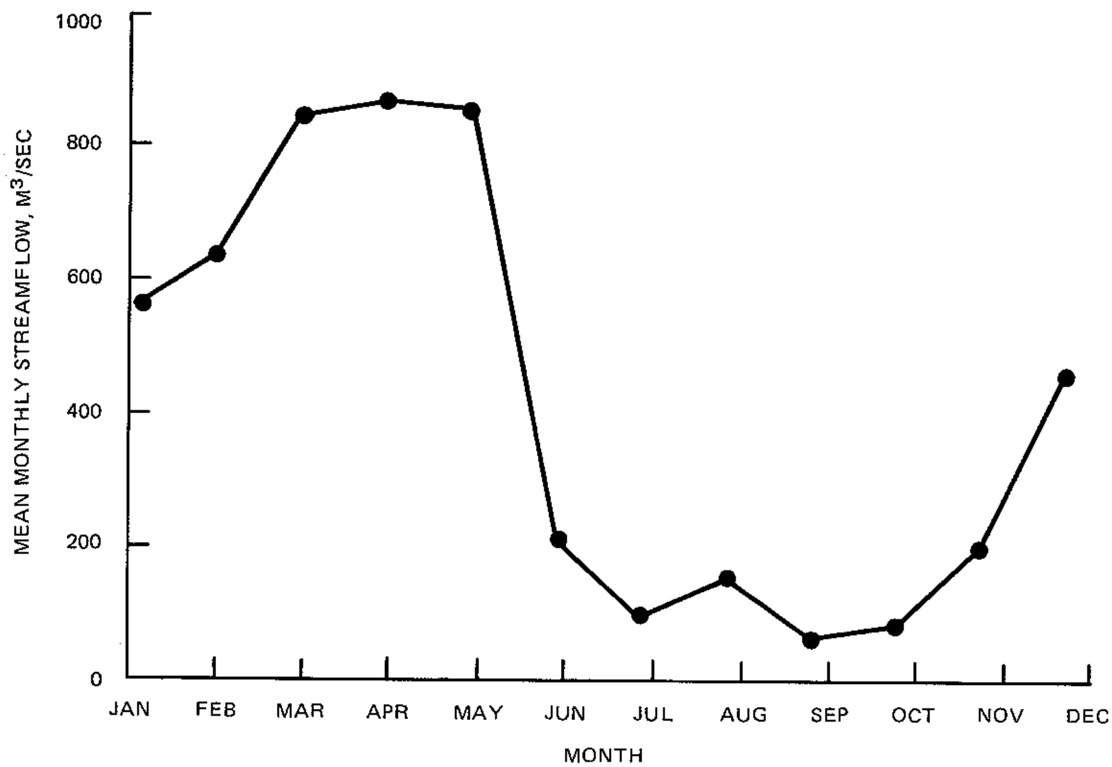

Figure 9. Typical mean monthly streamflow for an unregulated stream from 1963 to 1971. Note that flow is not constant throughout the year but tends to concentrate in winter and spring

be constructed across the stream to impound flood flows and release them gradually downstream at a decreased rate to reduce damage. The capacity of the reservoir reserved for floodwater storage could vary over the year to reflect the potential for flood damage at different seasons. Thus, the reservoir would be partially drawn down in late fall to vacate extra storage in anticipation of seasonal high flows in the stream. In fact, a 75-percent reduction in reservoir storage is not uncommon. Conversely, the reservoir could be partially filled in summer and still maintain a high level of flood protection. In addition, the reservoir surface elevation could be stabilized to enhance recreation in the pool. In some instances, reservoir storage may be used to augment downstream flows to protect a particularly valuable aquatic organism during the low-water season. Figure 10 is provided as a conceptual aid to understanding the allocation of storage within a typical flood control project.

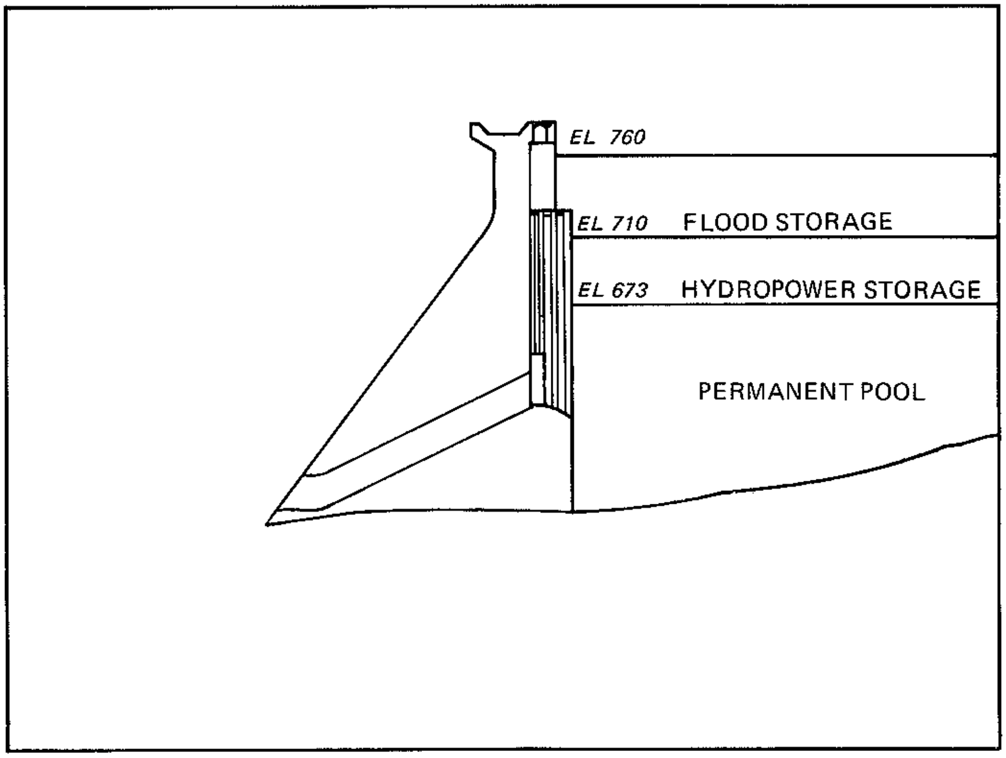

Figure 10. Storage allocation in a typical multipurpose CE reservoir project. Note that storage reflects project purposes, with flood storage being the reservoir volume maintained to intercept floodwaters.

4.1.4 For purposes of understanding downstream environmental effects, flood control operation can be broadly separated into two categories, high inflow (flooding) operation and low inflow (nonflooding) operation. Under low inflow conditions, reservoir discharge approximates inflow except during fall drawdown. Tailwater flows during fall drawdown exceed preimpoundment flows but generally remain within the river channel. During high inflow operation, reservoir discharges are shut off or reduced to allow the downstream reaches to clear because high discharges from the dam in addition to the inflows from the basin downstream of the project would result in flooding. After the downstream reaches have cleared, storm runoff is discharged as quickly as possible without causing downstream flooding. Peak flow rates during flood control operation are less than naturally occurring peak flood flows in an unimpounded river, but the high flows discharged from the project are for a longer duration than those occurring in unregulated streams. Late in spring, discharges are reduced to raise the reservoir to summer pool level.

4.1.5 Flood control operation also has the potential to modify physical habitat and water quality conditions in the tailwater from preimpoundment conditions, in addition to producing major alterations in monthly and seasonal flow patterns. In an unregulated stream, the composition of the channel bed reflects the dynamic equilibrium between deposition and erosion of sediments. However, in a regulated stream much of the sediment load of the inflows is deposited in the headwaters of the reservoir where turbulence and current velocity decrease substantially as the channel widens and deepens. Although the reservoir interrupts the downstream movement of sediment, releases from the dam continue to erode sediment from the tailwater. As a result, the tailwater becomes armored (i.e., a layer of coarse gravel, cobble, or rubble overlays the channel bed; see "Scour and Armoring," section 2.7) and degrades (decreases in elevation), unless an unregulated downstream tributary enters the tailwater (see "Sedimentation," section 2.8) or the channel flows over bedrock. The degree to which physical habitat in the tailwater is disrupted depends on the composition of the channel bed and banks. Channel beds and banks composed of large quantities of silt and sand tend to be more affected by armoring and channel degradation than channel beds composed predominantly of cobble or bedrock. Further physical changes in the channel can occur by encroachment of the channel by riparian vegetation since peak floods that would normally maintain the channel by uprooting and sweeping away riparian vegetation in unregulated streams are largely eliminated by flood control operation. Thus, not only is the capacity of the channel diminished, but roots, stems, and branches of riparian vegetation may become an important habitat feature of the tailwater.

4.1.6 The extent of seasonal water quality alteration caused by flood control operation is determined by chemical and physical conditions in the reservoir at the depth of withdrawal relative to preimpoundment conditions. In addition, passage of water through the reservoir outlets can further alter the quality of the water at the level of the intakes, particularly for dissolved gases such as oxygen.

4.1.7 Differences in water quality between the reservoir at the depth of withdrawal and the unregulated river are related to stratification patterns in the reservoir. In an unstratified reservoir, water temperatures within the reservoir change much more slowly than in a river (because a much greater volume of water must be heated and cooled), resulting in decreases in the amplitude of temperature fluctuations and delays in seasonal temperature change (see "Differences Between Tailwaters and Rivers," section 2.2). In a stratified reservoir, the nature of water quality alterations is largely determined by the depth of the intakes and the preimpoundment classification of the tailwater as a coldwater, coolwater, or warmwater fishery. These alterations are discussed in detail in section 2.4, entitled "Relative Effects of Surface Versus Deep Release"; however, the following trends are usually observed in the tailwater. Water released from the lower levels of a stratified reservoir in summer or early fall may be of poor quality, rich in nutrients and reduced substances, and cooler than preimpoundment temperatures. Water released from the upper levels of a stratified reservoir in summer or early fall is usually of good quality, contains low concentrations of nutrients and reduced substances, and is equal to or warmer than preimpoundment temperatures. Surface releases often contain substantial numbers of phytoplankton, zooplankton, and larval fish that may provide a food source for many tailwater organisms. Turbid water may be discharged into tailwaters after heavy rains or by density currents that flow through the reservoir.

4.1.8 The switch from a low-flow release to a high-flow release in a stratified reservoir may cause downstream water quality changes since the low-flow releases may be discharged from a gate located at a depth different than the high-flow releases. In some flood control reservoirs the high-flow releases are from the reservoir hypolimnion (if the reservoir is stratified), since the bottom sluice gates have the greatest capacity whereas the minimum flow releases are discharged from nearer the surface.

4.1.9 Operation of a reservoir project for flood control causes changes both in the downstream flow regime and downstream water quality. Types of release patterns that most commonly affect tailwater biota are seasonal low flows (minimum low-flow releases), high flows associated with flood control operation, and fall drawdown. Impacts of each of these operational procedures on biota are discussed in the following sections. Recommendations consistent with project purposes are provided to maintain the tailwater community, and methods to avoid some of the negative impacts of flood control operation are suggested. Effects of reservoir operation on water quality in the tailwater are discussed earlier in this handbook (sections 2.2 and 2.4) and are not discussed further in this part.

4.1.10 It should be noted that this part of the handbook discusses downstream effects commonly associated with many CE flood control projects. However, some aspects of flood control operation may be unique to a particular reservoir design or geographical area. For these aspects, the descriptions and recommendations can be used only as a general guide.

4.1.11 References

Davis, C. V., and Sorenson, K. E., eds. 1969. Handbook of Applied Hydraulics, McGraw-Hill Book Company, St. Louis, Mo.

Linsley, R. K., and Franzini, J. B. 1972. Water Resources Engineering, McGraw-Hill Book Company, St. Louis, Mo.

4.2 Impacts of Fall Drawdown

4.2.1 Topic Description

Flow in unregulated rivers is not constant throughout the year, but is generally concentrated in the winter and spring, although exceptions to this pattern are common. Storage in flood control reservoirs is evacuated, usually in late summer or early fall (fall drawdown), in anticipation of seasonal flooding. Discharge of high flows during fall drawdown can result in considerable changes from preimpoundment flow and water quality conditions.

4.2.2 Discussion

4.2.2.1 Fall drawdown results in changes from both preimpoundment water quality and flow conditions in the tailwater. In many unregulated rivers, the dry season historically occurs in late summer and early fall, and flows are generally lowest during this period of the year. However, river reaches downstream from flood control projects may receive sustained high flows as reservoir storage is evacuated in anticipation of winter and spring flooding. Although the flow regime during this time period is considerably altered from preimpoundment conditions, the detrimental effects of these flow alterations downstream from flood control projects have not been documented.

4.2.2.2 The timing of fall drawdown may have a significant effect on the biological dynamics of the tailwater ecosystem. Reservoirs generally destratify from October through December, depending upon latitude and seasonal meteorological conditions. Thus, in many situations, drawdown may occur either immediately before, immediately after, or during destratification. Downstream effects of fall drawdown are directly related to stratification patterns in the reservoir relative to the timing of drawdown. If fall drawdown occurs before destratification, the tailwater ecosystem may be subjected to poor water quality if deep floodgates are used to evacuate the reservoir. The reservoir hypolimnion may contain high concentrations of dissolved metals (iron and manganese), noxious gases (hydrogen sulfide), and low DO concentrations. Poor water quality of the releases can have a substantial negative effect on tailwater aquatic organisms. If fall drawdown occurs after destratification, then transport of contaminants into the tailwater may be reduced but many reservoir organisms will be transported through the sluiceway and into the tailwater. In some instances, fish from the reservoir may dominate the fish community in the immediate tailwater. From a fishery standpoint, this phenomenon has mixed effects. Reservoir fish may concentrate in the tailwater and thus provide a greater harvest for fishermen. However, this movement of large numbers of fish into the tailwater may disrupt the normal riverine assemblage of fish further downstream from the dam. The significance of the latter phenomenon has not been documented.

4.2.3 Recommendations

4.2.3.1 Two alternatives are available to maintain tailwater water quality during fall drawdown. If flood protection provided by the project is not jeopardized, fall drawdown can be scheduled after destratification to avoid subjecting tailwater biota to poor water quality. However this approach may have a negative impact on the reservoir fishery since there may not be enough growing season left to allow terrestrial vegetation to establish in the reservoir fluctuation zone. Terrestrial vegetation growing in the fluctuation zone of the pool provides desirable sites for fish spawning in the spring.

4.2.3.2 Alternatively, drawdown can be initiated gradually (without using the deep floodgate) in late summer using a combination of ports to blend water to achieve downstream water quality objectives. This approach has several advantages. First, it maintains flow in the tailwater closer to historical levels for the dry season. Second, it lengthens the growing season available for terrestrial vegetation to colonize the fluctuation zone, particularly the upper part of the fluctuation zone that will be exposed the earliest. However, the latter approach may have a negative impact on in-pool recreation since water levels will begin to fall during the latter part of the recreation season.

4.3 Impacts of Seasonal High Flows

4.3.1 Topic Description

Flood control projects reduce damage caused by high flows or stages in rivers by retaining flood flows until the downstream reaches have cleared. Once the downstream reaches have cleared (i.e., river levels have declined to less than flood stage), retained flows are released at a rate that evacuates the reservoir flood storage as quickly as possible without causing unacceptable downstream flooding. High discharges related to flood control operation (not fall drawdown) can occur in any season, but are most frequent in winter and spring. High discharges may affect tailwater aquatic biota.

4.3.2 Discussion

4.3.2.1 Large-volume discharges from dams associated with flood control operation differ significantly from preimpoundment flood flows. Reservoir flood releases have lower peak discharge rates and longer duration of high flows, and are usually restricted to the channel. The reduction in peak flows that results from flood control can have an effect on the shape of the channel. The peak flows that maintain the channel and sweep away riparian vegetation are replaced by lower, longer duration releases. Encroachment by riparian vegetation may eventually result in a reduction in channel capacity. However, in general, the downstream effects of flood releases have not been documented to be more deleterious to tailwater biota than preimpoundment flood flows.

4.3.2.2 The downstream effects of flood flows from a dam are substantially different from the effects of a minimum or base flow from a reservoir and may affect the biotic community in the river reaches downstream of the project. Important downstream effects associated with flood releases are increased water velocity and depth, potential poor summer water quality, increased scour and bank erosion, high turbidity, and changes in the composition of tailwater aquatic communities as reservoir organisms are flushed into the tailwater.

4.3.2.3 Increased water velocity and depth can change tailwater habitat. Pool-riffle associations in many tailwaters are changed to one long, deep, fast-flowing run with little or no backwater habitat. This habitat change reduces cover and shelter areas in the tailwater and may eliminate some organisms. Greater depth eliminates riffles and many riffle-dwelling species.

4.3.2.4 Greater water velocities dislodge and sweep downstream many aquatic macrophytes, periphyton, benthic invertebrates, and fish. Bank erosion associated with high water velocities can increase turbidity downstream. High velocities and turbidity can disrupt the reproduction of nesting fish species and can blow out salmonid redds. Increased turbidity also reduces light and thus shades out many aquatic plants, reducing the abundance of invertebrates and fish associated with aquatic plants. Most pool-dwelling species are restricted to areas sheltered from excessive velocities.

4.3.2.5 High flows during winter and fall flush reservoir-dwelling invertebrates and fish into the tailwater since, in winter, the reservoir is usually thermally and chemically mixed and many organisms are distributed throughout the water column. The volume of water discharged from the reservoir and the behavior of the reservoir species determine the number of organisms flushed into the tailwater. Nonmobile species (plankton), open-water fish species, and fish species attracted to currents around the discharge gates are most likely to be discharged into the tailwater. Impacts of flushing on tailwater biota include increased food for filter-feeding invertebrates and increased food for insectivorous and piscivorous fishes. Fish abundance in the tailwater increases, and crowding causes competition for space. Winter high flows are not generally associated with poor water quality.

4.3.2.6 Many flood control reservoirs are designed to release flood flows from a gate near the bottom of the reservoir. High flows released from the lower levels of a stratified reservoir may be devoid of oxygen and contain high concentrations of ammonia, manganese, and iron and other constituents potentially toxic to invertebrates and fish. Iron may flocculate, cover the substrate, and suffocate some organisms. Low

DO concentrations can be fatal to fish and invertebrates.

4.3.2.7 Flood control projects with multilevel outlet works have flood release capability only at the lower gate and smaller release capabilities at the higher level gates. These structures must release flood flows from the hypolimnion, which often is of poor quality during periods of stratification. The rapid temperature and chemical changes associated with change from an upper-level to a lower-level release can cause thermal and chemical shock.

4.3.3 <u>Recommendations</u>

4.3.3.1 Release of flood flows from a flood control project is an unavoidable part of flood control operation, and little opportunity exists to ameliorate the downstream effects of this operation. However, few effects of flood releases can be identified that are more deleterious than preimpoundment flood flows, with the possible exception of water quality changes associated with the change from an upper gate to a lower gate. Projects should be designed with selective withdrawal structures that can discharge most summer storms or efforts should be made, if possible, to change the release depth gradually to avoid chemical or thermal shock associated with rapid changes in release depth from a stratified reservoir. This can be done, if the design of the outlet structure permits, by keeping the upper ports open and opening the floodgate as slowly as possible during a gate change.

4.4 Impacts of Seasonal Low Flows

4.4.1 Topic Description

Flood control projects discharge seasonal (sustained) or short-term minimum low-flow releases as a normal part of flood control operation. Seasonal low flows are usually of long duration and may last several months. Ordinarily, minimum low-flow releases occur during the dry season (usually in summer and early fall) when the reservoir elevation is stabilized for summertime recreation by balancing discharge with inflow. However, since drought conditions may occur at any season, sustained minimum releases from a flood control project may also occur at any season. Short-term minimum low flows occur when releases from the dam would exacerbate flooding occurring downstream of the project. Extremely low (approaching zero) minimum flow releases have the potential to severely stress tailwater aquatic organisms. Consequently, estimating the minimum low-flow release that maintains the tailwater aquatic community becomes a legitimate concern in the operation of a reservoir project.

4.4.2 Discussion

4.4.2.1 Minimum low-flow releases can stress tailwater aquatic organisms in a number of ways. The effects of minimum releases on downstream biota associated with flood control operation are generally similar to the effects of minimum low flows (particularly the short-term minimum low flows) associated with peaking hydropower operation. Refer to paragraph 3.2.2.1 for an overview of these effects.

4.4.2.2 Establishment of a suitable minimum low-flow release will alleviate many detrimental impacts associated with seasonal and short-term low-flow or no-flow periods. A quantity of habitat is maintained for tailwater biota, and crowding and increased competition for food and space associated with an inadequate low flow are avoided. Minimum reservoir releases alleviate low DO concentrations resulting from respiration of tailwater biota in stagnant pools and slow the otherwise rapid warming of coldwater releases. Minimum flows maintain the supply of oxygen and drifting food to filter-feeding insects, thus maintaining some fish food.

4.4.2.3 There are two general approaches for determining the minimum reservoir releases necessary to sustain tailwater biota. These approaches are discussed in paragraphs 3.2.2.6-3.2.2.8.

4.4.2.4 In addition to flow modification, physical changes (habitat improvement) can be used to increase the habitat available downstream from reservoir projects during seasonal minimum low flows. Further details on methods to improve instream habitat can be found in Shields and Palermo (1982). An example of a habitat improvement downstream from a reservoir is excavating deep pools in the tailwater to provide habitat for aquatic biota during seasonal minimum low flows. Pools should be connected to allow fish passage during low flows. Wing dikes can concentrate flows to the center of the channel if increased water velocity is required. Areas behind the wing dike can provide shelter to tailwater fish during high flows.

4.4.2.5 Several factors must be considered during the course of formulating release recommendations from a reservoir project for downstream environmental quality enhancement. First, the reservoir is being operated to reduce flood damage and save lives and property. Minimum low-flow requests to maintain tailwater aquatic habitat cannot jeopardize the capability of the project to control downstream flooding.

4.4.2.6 Second, the reservoir surface elevation is partly determined by the discharge patterns of the project. If discharges exceed inflows, then the reservoir surface elevation (and surface area and volume) decrease. Conversely, if inflows exceed discharges and withdrawals, the reservoir surface elevation (and surface area and volume) must increase. Since the reservoir fishery dynamics are largely determined by seasonal water-level fluctuations, efforts to enhance downstream habitat by increasing discharges during drought conditions may have a detrimental effect on the reservoir fishery. Additionally, in nonhydropower flood control projects, many of the tailwater fish are recruited from the reservoir (see Jacobs et al. 1985 for details). Thus, efforts designed to increase populations of tailwater fish by releasing greater flows from the reservoir may have just the opposite effect if the reservoir fishery is damaged to the extent that recruitment into the tailwater is affected. Therefore, the effects of efforts to optimize conditions for the fish populations downstream of the reservoir must be balanced against the effects these efforts have on the reservoir fishery. If possible, the reservoir and downstream reaches should be managed as an integrated unit. Methods to assess the effects of seasonally fluctuating water levels on reservoir fish can be found in Ploskey (1982, 1983) and Ploskey, Nestler, and Aggus (1984).

4.4.2.7 Third, most (but not all) CE projects are fundamentally different from the projects originally associated with the instream flow issue. These projects were used primarily to provide for irrigation and water supply (out-of-stream uses) whereas in most CE projects the water remains in the system. Thus, the issue for nonhydropower flood control projects is not how much water should be allocated for fisheries but rather, what is the optimum seasonal release pattern recognizing that water can be neither added to nor subtracted from the system nor can the authorized purpose of the project be jeopardized.

4.4.2.8 Fourth, most nonhydropower flood control projects are constructed on tributary streams in which the historical minimum low flow was probably zero or close to zero. Therefore, minimum low-flow releases from a nonhydropower flood control project are probably greater than preimpoundment minimum low flows. The quantity of minimum release should not ordinarily be as critical an issue downstream from a flood control project as potential water quality changes, since low-flow conditions with the project in place are generally better than preimpoundment low-flow conditions.

4.4.2.9 Fifth, most commonly used methods to determine flow regimes to maintain downstream organisms are based on the concept of a "target species," that is, a species of aquatic organism that is valuable in its own right or representative of the requirements for the entire community. The selection of appropriate target species is one of the most important considerations in determining the downstream flow needs of the aquatic community. Further information on this topic is provided in section 2.9, "Target Species Selection."

4.4.3 Recommendations

4.4.3.1 Performance of an instream flow study to determine the flow requirements of tailwater organisms should be considered to protect a valuable downstream fishery resource from effects of seasonal or short-term low flows. For most CE applications, the Physical Habitat Simulation (PHABSIM) system is the most defensible method for determining instream flow requirements to maintain aquatic biota, but is also the most difficult to perform. Detailed guidance on the performance of an instream flow study is beyond the scope of this handbook, and the user should consult Bovee (1982) and Milhous, Wegner, and Waddle (1984) for further information on this topic.

4.4.3.2 General guidance can be provided to help ensure that the most defensible study is performed. An instream flow study is a complex undertaking that involves a knowledge of aquatic ecology, fishery biology, hydraulic simulation, water quality modeling, and potamology. Ordinarily, a single individual or even a single agency lacks the technical expertise to adequately perform a defensible study, particularly for a complex river system. Thus, an instream flow study should be viewed as a multidisciplinary, cooperative effort between agencies whose mission includes responsibility for the stream in question. This approach also ensures that most of the institutional misunderstandings between agencies that may arise concerning an instream flow study can be resolved during the course of the study rather than at the conclusion of the study, during the review process. To this end, an instream flow study sponsored by the CE should include in the study team one knowledgeable representative of the CE District office.

4.4.4 References

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